American Mineralogist, Volume 80, pages 1343–1346, 1995

The Stillwater Complex, Montana: A subvolcanic magma chamber?

ROSALIND TUTHILL HELZ
U.S. Geological Survey, M.S. 107, Reston, Virginia 22092, U.S.A.

ABSTRACT

Five magma types occur as sills in the footwall of the Stillwater Complex, all of them coeval with the Stillwater in age. Two of the magma types have compositions that suggest they are similar to the magmas from which the cumulates of the Stillwater's Basal and Ultramafic series crystallized. Melting experiments performed on samples of these two magma types and on a 50–50 mix of the two types show that the crystallization sequence inferred from the Ultramafic series cumulates (olivine > orthopyroxene > plagioclase > augite) is matched only in the mixture of the two sill types at 1.5–3 kbar. Thus, the observed stratigraphy of the Basal and Ultramafic series may result from mixing of two distinct magmas rather than fractionation of a single magma. The permissible pressure range of 1.5–3 kbar implies that the depth of the Stillwater magma chamber was similar to that of subvolcanic magma chambers such as that of Kilauea Volcano, which raises the possibility that the Stillwater magma body may also have been a subvolcanic reservoir.

INTRODUCTION

One obstacle to deciphering the magmatic history of layered mafic intrusions is that it is not easy to identify the compositions of the parental magmas from which the cumulates were precipitated. Most layered complexes are accompanied by finer grained satellite intrusions, but the relationship between the compositions of the smaller bodies and the compositions of the magmas parental to the cumulates is usually not straightforward (see, e.g., Sharpe, 1981; Cawthorn et al., 1981). If the layered intrusion is itself complete, its bulk composition may be inferred by summing up the individual layers, assuming that the intrusion represents a closed system. Incomplete sections, and the possibility of open-system behavior, make the problem considerably more difficult for most intrusions.

The Stillwater Complex of Montana is a large layered mafic intrusion, which has lost its upper part to erosion. The preserved cumulates include the Basal series (dominated by cumulates of orthopyroxene ± plagioclase: see Hess, 1960; Page, 1979) followed by the Ultramafic series (see, e.g., Jackson, 1961; Raedeke and McCallum, 1984). The latter unit has been subdivided (Zientek et al., 1985) into the Peridotite zone (olivine + orthopyroxene cumulates occurring in cyclic units) and the Bronzitite zone (orthopyroxene cumulates). These mafic and ultramafic layers are overlain by a thick section of plagioclase-rich cumulates, the Banded series (Hess, 1960; McCallum et al., 1980). The upper contact of the Stillwater has not been preserved, however, so some fraction of the upper part of the Complex has been removed by erosion (Hess, 1960). For many years the Stillwater cumulates were considered to have been produced by the very efficient, closed-system fractionation of a single magma (Hess, 1960; Jackson, 1961, 1970). With this assumption in mind, and on the basis of a limited number of analyzed chill samples, Hess (1960) inferred that 40% of the Complex has been removed by erosion. More recently, it has been recognized that many cumulates of the Banded series must have been derived from a magma different from that which produced the lower cumulates (see e.g., McCallum et al., 1980), which makes Hess's approach to estimating what has been lost to erosion less viable.

CANDIDATE PARENTAL MAGMAS FOR THE BASAL AND ULTRAMAFIC SERIES

The footwall of the Stillwater Complex contains a mafic sill swarm, formerly included in the Basal series. Though now excluded (Zientek et al., 1985) from the Complex proper, these sills are closely associated with the Complex in space (Page, 1979; Zientek, 1983) and time (Premo et al., 1990; DePaolo and Wasserburg, 1979). The five independent magma types found in the Basal sill swarm have been characterized petrographically, chemically, and isotopically (Helz, 1985; Zientek, 1983; Lambert et al., 1994). Two are magnesian (Helz, 1985), enriched in light rare earth elements (LREE) (Helz, 1985; Lambert and Simmons, 1987), and have ϵ_{Nd} values (Lambert et al., 1994) similar to those of the Ultramafic series cumulates, characteristics that make them candidate parental magmas for the Basal and Ultramafic series cumulates. Calculations using the method of Ghiorso (1985) suggested that a 50:50 mix of the two magnesian sill types might have a more Stillwater-like crystallization sequence than either type alone. The compositions of the two samples used as starting materials and that of the 50:50 mix are shown in Table 1.

0003–004X/95/1112–1343$02.00

Table 1. Bulk silicate compositions of sills used as experimental starting materials

	1 Mafic norite*	2 Mix 50:50**	3 Magnesian gabbronorite†
SiO_2	53.10	51.90	50.70
TiO_2	0.44	0.73	1.02
Al_2O_3	11.20	13.20	15.20
Σ FeO	14.70	12.72	10.74
MnO	0.18	0.18	0.18
MgO	12.70	11.02	9.33
CaO	7.00	8.50	10.00
Na_2O	0.41	1.11	1.83
K_2O	0.19	0.27	0.34
P_2O_5	0.08	0.09	0.10
Sum	100.00	99.72	99.45
S content	1.68	0.85	0.02

* Mafic norite sample 81VCZ-23. The sample consists of orthopyroxene, plagioclase, minor augite and ilmenite, and trace amounts of chromite and apatite. It also contains about 4% sulfide. The S in the bulk analysis was calculated as FeS, and omitted from the renormalized analysis, to give a clearer picture of the bulk silicate composition. H_2O was also omitted in the renormalization.

** Mixture of rock powders shown in columns 1 and 3. The mixture contains about 2% sulfide. S in the bulk analysis was handled as in column 1.

† Magnesian gabbronorite sample NB18/374. The sample contains orthopyroxene, plagioclase, augite, minor ilmenite, and trace amounts of biotite, apatite, and sulfide.

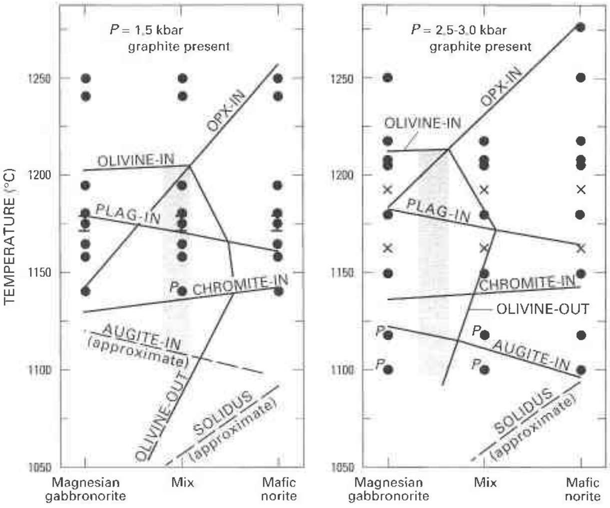

Fig. 1. Experimentally determined phase relations of the compositions shown in Table 1, as a function of temperature and composition, at 1.5 kbar (**left**) and 2.5–3.0 kbar (**right**). The samples were contained in Fe-saturated platinum capsules; the f_{O_2} of the samples was defined by the graphite + CO + CO_2 buffer. The shaded region shows the location of the crystallization sequence olivine > orthopyroxene > plagioclase > augite. Brackets around a symbol indicate temperature uncertainties that include a contribution from a temperature gradient; the uncertainty in temperature from other sources is ±10 °C. The "X" symbols on the 2.5–3.0 kbar *T-X* section show the position of two experiments performed at 2.5–2.6 kbar. Symbols marked with "*P*" indicate Ca-poor pyroxene that is pigeonite rather than orthopyroxene. All assemblages in the mafic norite and the mix contain immiscible sulfide liquid in addition to the phases indicated.

Experimental results and discussion

The crystallization sequences of these three compositions at 1.5 and 3.0 kbar are shown in Figure 1. The sequence of crystallization for the major silicate minerals (olivine > orthopyroxene > plagioclase > augite) that matches the sequence inferred for the lower parts of the Stillwater is observed in the 50:50 mix at 1.5 kbar and can be inferred to occur in slightly different mixing ratios at 3 kbar, as indicated in Figure 1. Compositions of the near-liquidus olivine and orthopyroxene are Fo_{79-80} and En_{79-81}, which match the observed compositions of olivine and orthopyroxene in the lowermost part of the Peridotite zone (Raedeke and McCallum, 1984; Loferski et al., 1990). The principal difference between the experimental results and the crystallization sequence inferred from the cumulates is the late crystallization of chromite in the experiments vs. its ubiquity in the Peridotite zone. This results from the use of graphite to control f_{O_2} during the experiments and confirms earlier inferences (Mathez et al., 1989) that although parts of the Stillwater Complex contain graphite, the f_{O_2} in the early stages of its development was higher and evolved toward graphite saturation with time.

The *T-X* relations show that neither of the naturally occurring liquids could serve as sole parent to the Basal and Ultramafic series in this pressure range. Olivine, the characteristic cumulus mineral of the Peridotite zone, is completely absent from the crystallization range of the mafic norite at and above 1.5 kbar. The magnesian gabbronorite by itself can be ruled out as a parent because orthopyroxene in gabbronorite begins to crystallize only at the same temperature as plagioclase at 3 kbar and at lower temperatures at lower pressures. The desired sequence should exist in the magnesian gabbronorite just above 3 kbar; however, olivine does not disappear in that composition until $T < 1100$ °C, far below the first appearance of both plagioclase and augite, which is inconsistent with the phase relations observed in the Stillwater cumulates. Only intermediate mixtures of the two liquid types exhibit the right crystallization behavior at reasonable pressures.

Figure 2 shows how the position of the olivine-orthopyroxene boundary shifts with pressure, relative to the 1 atm phase relations, in the system Fo-An-SiO_2. By 1.5 kbar, the boundary shifts to near the position of the mix; at 3.0 kbar it lies between the mix and the magnesian gabbronorite compositions, essentially coinciding with the enstatite-anorthite join, a position not reached in the Fe-free system until 10 kbar (Sen and Presnall, 1984). This means that the boundary is no longer a peritectic, but a cotectic boundary, and the reaction of olivine with the liquid to produce orthopyroxene no longer occurs at near-liquidus conditions. This shift in the position of the olivine-orthopyroxene boundary places an upper limit on the pressure at which the Ultramafic series could have crystallized, as resorption of olivine next to orthopyrox-

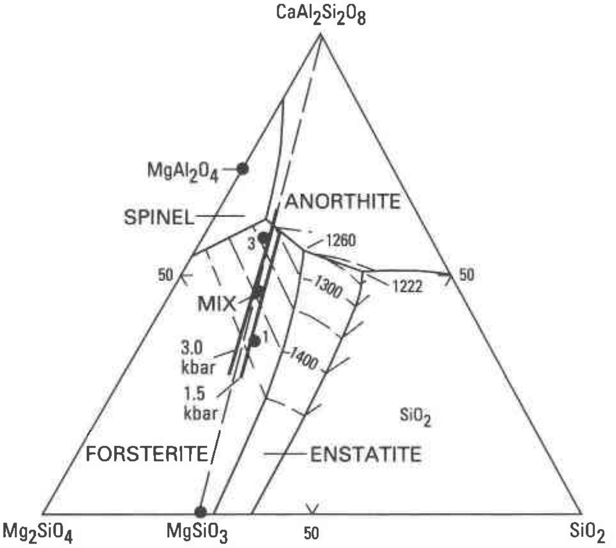

Fig. 2. The plane forsterite(Fo)-anorthite(An)-SiO_2, in weight percent. Short dashed lines are isotherms and light solid lines are the phase boundaries at 1 atm, both as determined by Andersen (1915). The compositions in Table 1 are shown by the black circles. The heavy solid lines show the position of the olivine-orthopyroxene boundary for these compositions at 1.5 and 3.0 kbar, as deduced from the experimental results shown in Fig. 1. Note that by 3.0 kbar, this boundary coincides with the compositional join between enstatite (orthopyroxene) and anorthite (marked by long dashes).

ene is observed in the Ultramafic series (Jackson, 1961; Raedeke and McCallum, 1984). The present results suggest that total pressure at the base of the Stillwater chamber was <3.0 kbar during formation of the Ultramafic series.

IMPLICATIONS FOR THE STILLWATER COMPLEX

The Stillwater's inferred crystallization sequence is based in part on the nature of the cyclic units in the Peridotite zone (Jackson, 1961, 1970). The observation that this sequence is reproduced only in a hybrid composition (Fig. 1) at reasonable pressures suggests that the Peridotite zone may be the product of mixing of the two distinct liquids rather than the repeated intrusion of only one. Comparison of the phase relations calculated for the mafic norite with those observed in Figure 1 suggests that olivine replaces orthopyroxene on the liquidus of that composition somewhere between 0.5 and 1.0 kbar, at which point the desired Stillwater crystallization sequence would be produced in that one liquid. However, the orthopyroxene-rich Basal zone cumulates and those of the Bronzitite zone could be derived from the mafic norite magma type alone at 1.5–3.0 kbar. To produce the olivine cumulates of the Peridotite zone at the same pressures that obtained during crystallization of the underlying Basal zone and the overlying Bronzitite zone requires the presence of a second, less siliceous magma.

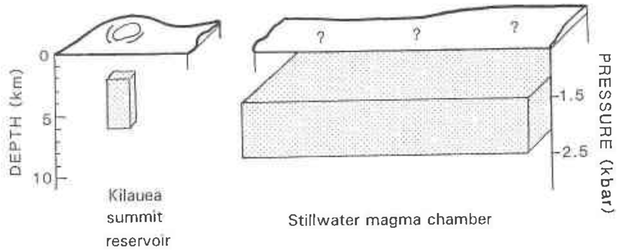

Fig. 3. Sketch showing the relative sizes and approximate depths of the summit reservoir of Kilauea Volcano and the Stillwater magma chamber. The vertical exaggeration is 2:1.

The two-liquid model has several advantages over single-magma models for the origin of the Basal and Ultramafic series. It offers an explanation for the Fe-rich nature of the first cumulus olivine (Fo_{79}) to appear at the base of the Peridotite zone, for the abrupt disappearance of olivine [still at its peak Mg/(Mg + Fe) content of Fo_{85}] at the top of the Peridotite zone, and for the fact that no major discontinuity in Mg/(Mg + Fe) in the cumulus minerals is observed at either stratigraphic position (Raedeke and McCallum, 1984); all these features are very difficult to explain by fractionation of a single liquid. In a magma-mixing model, the shift to olivine-dominant cumulates within the Peridotite zone would be produced by a change in the mixing ratio, and hence of SiO_2 activity, of the two liquids in the recharge, from nearly 100% mafic norite to >50% magnesian gabbronorite, not by the arrival of less-differentiated liquid. The loss of olivine at the top of the Peridotite zone would not reflect fractionation (for which there is no evidence in the Mg′ of the cumulates) but either a decrease in the fraction of the gabbronorite relative to the mafic norite or its complete loss as a component of the new magma entering the chamber. This model is also more consistent with the heterogeneity of REE patterns in Ultramafic series cumulates (Lambert and Simmons, 1987), and with their isotopic heterogeneity (Lambert et al., 1994), than models invoking a single parent for the Ultramafic series. Lastly, it is consistent with the observed presence of two magnesian sill types in the footwall of the Complex, neither of which by itself has the right composition to be the parental magma. The absence of hybrids among the footwall sills implies that the mixing took place in the Stillwater chamber itself.

The upper pressure limit of 3 kbar found here is consistent with *P-T* conditions inferred from contact metamorphic assemblages in the footwall hornfelses (825 °C, 3 ± 0.5 kbar; Vaniman et al., 1980; Labotka, 1985), if one assumes those conditions represent reequilibration during post-Stillwater cooling of the contact aureole; the pressure in the footwall at the end of the development of the Stillwater Complex can only have been higher than it was during the development of the Ultramafic series. The inferred pressure of formation of the Ultramafic series (1.5–3.0 kbar) requires that the magma chamber was relatively shallow (approximately 3–9 km). This is similar to the 2–6 km depth of the main part of the summit reservoir of Kilauea Volcano (Ryan, 1981), one of the most active volcanoes in the world. The cross-sectional area of Kilauea's reservoir is inferred to be about 2 × 2 km (Ryan, 1981), whereas that of the Stillwater is at least 40 × 20 km (Hess, 1960; Brodzowski, 1985), as shown in Figure 3. Given that the Stillwater Complex was two orders of magnitude larger than Kilauea's reservoir, and that its inferred depth was not much greater, it seems quite possible that the Stillwater was a subvolcanic magma chamber, as inferred by Lipin (1993). It presumably underlay a sizeable plateau of mafic lavas. If so, it seems likely that much of the missing material of the complex would not be eroded cumulates but a long-vanished volcanic carapace.

ACKNOWLEDGMENTS

I wish to thank D.L. Hamilton, Senior Lecturer in Geology at the University of Manchester, in whose laboratory these experiments were performed. I am also grateful for the assistance of B. Kjaersgaard and J. Small for their assistance. The paper benefitted from reviews by B.R. Lipin, J.S. Huebner, J.S. Pallister, G.K. Czamanske, S.B. Shirey, and M.L. Zientek.

REFERENCES CITED

Andersen, O. (1915) The system anorthite-forsterite-silica. American Journal of Science (Fourth Series), 39, 407–454.

Brodzowski, R.A. (1985) Cumulate xenoliths in the Lodgepole, Enos Mountain and Susie Peak intrusions: A guide. In Montana Bureau of Mines and Geology Special Publication, 92, 368–372.

Cawthorn, R.G., Davies, G., Clubley-Armstrong, A., and McCarthy, T.S. (1981) Sills associated with the Bushveld Complex, South Africa: An estimate of the parental magma composition. Lithos 14, 1–16.

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.

Ghiorso, M.S. (1985) Chemical mass transfer in magmatic processes: I. Thermodynamic relations and numerical algorithms. Contributions to Mineralogy and Petrology, 90, 121–141.

Helz, R.T. (1985) Composition of fine-grained mafic rocks from sills and dikes associated with the Stillwater Complex, Montana. In Montana Bureau of Mines and Geology Special Publication, 92, 97–117.

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

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.

——— (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. Geological Society of South Africa, Special Publication 1, 391–424.

Labotka, T.C. (1985) Petrogenesis of the metamorphic rocks beneath the Stillwater Complex: Assemblages and conditions of metamorphism. In Montana Bureau of Mines and Geology Special Publication, 92, 70–76.

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.

Lambert, D.D., Walker, R.J., Morgan, J.W., Shirey, S.B., Carlson, R.W., Zientek, M.L., Lipin, B.R., Koski, M.S., and Cooper, R.L. (1994) Re-Os and Sm-Nd isotope geochemistry of the Stillwater Complex, Montana: Implications for the petrogenesis of the J-M reef. Journal of Petrology, 35, 1717–1753.

Lipin, B.R. (1993) Pressure increase, the formation of chromite seams, and the development of the Ultramafic series in the Stillwater Complex, Montana, Journal of Petrology, 34, 955–976.

Loferski, P.J., Lipin, B.R., and Cooper, R.W. (1990) Petrology of chromite-bearing rocks from the lowermost cyclic units in the Stillwater Complex, Montana. U.S. Geological Survey Bulletin, 1674-E, 1–28.

Mathez, E.A., Dietrich, V.J., Holloway, J.R., and Boudreau A.E. (1989) Carbon distribution in the Stillwater Complex and evolution of vapor during crystallization of Stillwater and Bushveld magmas. Journal of Petrology, 30, 153–173.

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.

Page, N.J. (1979) Stillwater Complex, Montana: Structure, mineralogy, petrology of the Basal zone with emphasis on the occurrence of sulfides. U.S. Geological Survey Professional Paper, 1038, 69 p.

Premo, W.R., Helz, R.T., Zientek, M.L., and Langston, R.B. (1990) U-Pb and Nd-Sm ages for the Stillwater Complex and its associated sills and dikes, Beartooth Mountains, Montana: Identification of a parent magma? Geology, 18, 1065–1068.

Raedeke, L.D., and McCallum, I.S. (1984) Investigations in the Stillwater Complex: Part II. Petrology and petrogenesis of the Ultramafic series. Journal of Petrology, 25, 395–420.

Ryan, M.P. (1981) Modeling the three-dimensional structure of macroscopic magma transport systems: Application to Kilauea Volcano, Hawaii. Journal of Geophysical Research, 86, 7111–7129.

Sen, G., and Presnall, D.C. (1984) Liquidus phase relationships on the join anorthite-forsterite-quartz at 10 kbar with applications to basalt petrogenesis. Contributions to Mineralogy and Petrology, 85, 404–408.

Sharpe, M.R. (1981) The chronology of magma influxes to the eastern compartment of the Bushveld Complex as exemplified by its marginal border groups. Journal of the Geological Society of London, 138, 307–326.

Vaniman, D.T., Papike, J.J., and Labotka, T. (1980) Contact-metamorphic effects of the Stillwater Complex, Montana: The concordant iron formation. American Mineralogist, 65, 1087–1102.

Zientek, M.L. (1983) Petrogenesis of the Basal zone of the Stillwater Complex, Montana. Ph.D. thesis, Stanford University, Stanford, California.

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

MANUSCRIPT RECEIVED JUNE 24, 1995
MANUSCRIPT ACCEPTED SEPTEMBER 20, 1995