The Stillwater Complex, Montana: The root of a Flood Basalt Province?

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We have estimated the amount of magma that passed through the Stillwater Complex to form its Ultramafic series. The estimate ranges from 70,000 to 233,000 km^3. By comparison, the eruptive volume of the Colombia River flood basalt province is 170,000 km^3.

The Stillwater Complex is an Archean mafic-ultramafic layered intrusion that can be subdivided into 5 stratigraphic units. The lowermost, the Basal Series, is up to 100 m thick and consists predominantly of orthopyroxene cumulates. Cu-Ni deposits occur at its base. Next in section, the Ultramafic Series, is about 1400 m thick and consists of ultramafic cumulate rocks. Chromite seams are found in cyclic units in the lower part of this package of rocks. The Lower, Middle, and Upper Banded series, approximately 4000 m thick, consist of rocks containing cumulus plagioclase. The PGE-rich JM Reef occurs in the Lower Banded series.

Several lines of evidence suggest that the top of the complex was very close to or even at the Earth's surface and venting of Stillwater magmas almost certainly took place. Even though the upper contact of the complex has been removed by erosion, up to 6 km of layered rocks are exposed. Labotka and Kath (2001) estimated the depth of emplacement to be 6-7 km from thermodynamic analysis of the mineral assemblages in the hypersthene hornfels and cordierite-cummingtonite hornfels in the thermal aureole at the base of the complex. These results are consistent with estimates from melting experiments conducted to investigate the bulk composition and crystallization relations of the Stillwater Complex. These experiments limit the pressure of formation of the Ultramafic series to 1.5 to 3.0 kb (Helz, 1995). This would imply that the magma chamber was relatively shallow (about 3 to 9 km). The exposed stratigraphic thickness of the complex, when combined with the depth estimates, suggests that the top of the complex relatively close to the surface. About 20 cyclic units compose much of the Ultramafic series, and most workers interpret their presence as an indication that the magma chamber filled and vented many times. However, erosion appears to have removed the mafic magmas that almost certainly vented to the surface 2.7 billion years ago.

The area of the complex, the thickness of the Ultramafic series, and the amount of fractionation that took place to form the cyclic units constrain the volume of magma. The area of the complex, as determined by gravity and magnetics, is 2500 to 5000 km^2 (Bonnini, 1982, Kleinkopf, 1985). From measured sections, the average thickness of the Ultramafic series is 1400 m (Jones and others, 1960). The amount of fractionation that took place can be estimated if we can estimate the original composition of the magma and determine the change in (Mg/Mg+Fe) that took place in olivine and orthopyroxene in the cyclic units. We can then use the method developed by Irvine (1979) to calculate the percent fractionation that took place in the cyclic units.

Table 1. *Size of the Ultramafic series of the Stillwater Complex and estimates of the volume of magma that passed through it assuming 3 and 5 percent crystallization.*

Estimates of area of Stillwater Complex, at present (km^2)	Average thickness of the Ultramafic series, at present (km)	Volume of magma erupted at 5 % (km^3)	Volume of magma erupted at 3 % (km^3)
2500	1.4	70 000	120 000
4400*	1.4	120 000	210 000
5000	1.4	140 000	233 000

**Preferred estimate according to Bonini (1982).*

From detailed study of the very small amount of change in Mg/(Mg+Fe) in the cumulate olivine and orthopyroxene (Mg# =.86-.84), we conclude that no more than three to five percent fractionation took place during the deposition of the Ultramafic series (Loferski and others, 1990, Campbell and Murck 1993). Thus, 95 to 97 percent of the liquid was probably vented.

The magma did not simply rise up in the chamber and continue to fractionate for two reasons. First, if no magma escaped, the Stillwater Complex would have been 28-47 km thick. Second, the crystallization sequence in most of the overlying Banded series is different from that of the Ultramafic series, indicating a second magma with a different composition. Thus, most of the overlying Banded series was not derived from the continued fractionation of the magma that formed the Ultramafic series. Given the dimensions and an estimate of the fraction of liquid vented, we arrive at the volume extruded, summarized in table 1.

These estimates are minimum values for the eruptive volume from the Stillwater Complex for the following reasons:

1. The Ultramafic series is only about 20 percent of the thickness of the entire complex. We do not yet have a method to estimate the volume of expelled magma from the Banded series.
2. The estimate for the area occupied by the Stillwater Complex is the present day area. The original area was probably greater than it is now.
3. This estimate assumes that every influx of magma into the chamber had a long enough residence time in the chamber to fractionate three to five percent. However, there is evidence in some parts of the stratigraphy, especially in the lower part, that magma entered and spent only a relatively small amount of time and probably underwent even less fractionation than three to five percent.

The estimate for the amount of magma needed to form the Ultramafic series places it among the smaller of the flood basalt systems as shown by table 2.

The parent composition of the Stillwater Complex, as determined by Helz (1995), is unlike any known large igneous province. That may be explained by the fact that the Stillwater Complex, if it were the root of a flood basalt province, would be the oldest of these provinces (see table 2). Its composition is compatible with the compositions of Archean and Proterozoic siliceous high-magnesium basalts (Sun and others, 1989; table 3).

Our interpretation of the Stillwater Complex helps to establish the magmatic and tectonic framework in which the complex formed. In this context, the Stillwater Complex can be compared to other large-igneous province systems: (1) the 2.45 Ga event that formed layered intrusions throughout Finnoscandian shield; (2) the 1.3 Ga event that formed the Muskox intrusion, the Coppermine basalts, and the Mackenzie dike swarm; and (3) the 1.1 Ga event that formed the Duluth Complex and the Keweenawan lavas. Associating ore deposits to these larger magmatic systems should help the development of deposit models for magmatic ore deposits.

Table 2. *Age, eruptive volume of selected flood basalt provinces.*

Province	Age (Ma)	Estimated volume (10^6 km^3)
Columbia River	6-17.5	0.17
Ethiopian	21-32	0.35
North Atlantic	45-65	2-10
Deccan	60-65	1.5
Manihiki	~110	13
Ontong-Java	90-122	19
Parana Etendeka	120-135	1.5
Siberian	230-235	1.5
Keweenawan	1094-1109	0.85
Stillwater	**2700**	**0.084-0.233**

Table 3. *Estimated Composition of the parent magma of the Ultramafic series in the Stillwater Complex to other Archean siliceous, high-mg magmas.*

	Stillwater Parent Magma (Helz, 1995)	**Fennoscandian Intrusions (Saini_Eidukat and others, 1997)**	**Negri Volcanics, Western Australia 331/338 (Sun and others, 1989)**	**Vestfold Hills, Eastern Antarctica 65280007 (Sun and others, 1989)**
SiO_2	51.60	51.29-57.38	55.39	55.7
TiO_2	0.73	0.13-1.05	0.43	0.67
Al_2O_3	12.95	3.08-19.66	11.69	11.07
FeO	13.35	6.75-12.27		
Fe_2O_3			10.26	11.36
MnO	0.18	0.09-0.32	0.22	0.16
MgO	10.81	4.74-22.78	12.26	10.67
CaO	8.45	3.25-12.09	7.86	7.05
Na_2O	1.11	0.11-3.95	1.92	1.48
K_2O	0.27	0.01-5.73	0.48	1.14
P_2O_5	0.09	0,015-0.078	0.04	0.09
SUM	99.54		100.55	99.39
MG #	0.60	0.581-0.854		

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