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## Geology of the Uppermost Outcrops of the Stillwater Complex in the Boulder River Valley, Montana

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We have examined outcrops of some of the uppermost rocks of the Stillwater Complex that occur in a small area on the west side of the Boulder River Valley. The rocks in these outcrops exhibit a wide range of grain size and texture, and include many layers of fine-grained gabbro-norite that do not have cumulate textures. A similar association of rock types has been described at the top of the Picket Pin section in the central part of the Stillwater Complex (Carlson and Zientek, 1985). The purpose of our work was to delineate the relationship between the fine-grained, noncumulate rocks and the adjacent cumulates in the Boulder River outcrops, in order to better understand the significance of the noncumulate rocks, both here and elsewhere in the Complex.

The outcrops, extending over an area of 600 x 1300 feet (200 x 400 m) consist of a series of low ledges and ridges, rounded by glaciation and partially draped with glacial debris and colluvium. There are no outcrops of Stillwater Complex rocks further north or west of the mapped area. To the south, the sole unit exposed (outside the area mapped) is a massive, pyroxene-rich gabbro-norite, with plagioclase the only mineral having a cumulate texture. We have made an outcrop map of this area, and collected 58 samples for petrography and chemical analysis. In addition to major-element analyses of 28 samples from the Boulder River outcrops, we have major-element analyses of 15 samples from the equivalent section at Picket Pin, the easternmost known occurrence of this association. Because the Stillwater Complex is eroded more deeply to the east, rocks this high in the stratigraphy of the Complex are only found in the western third of the complex.

The outcrop map shows that layers of both the coarse, cumulate rocks and the fine-grained noncumulate rocks are quasi-conformable locally, with lateral continuity over 600 feet or more, in the central to western part of the mapped area. Most individual layers of both cumulate and noncumulate rocks range from 10-60 feet (3-18 m) thick. In the upper part of the section, the map pattern suggests that the fine-grained material has disaggregated and digested the cumulate material, replacing and obliterating a layer of plagioclase-rich cumulate 20-

30 feet (6-9 m) thick. The discontinuous bodies of cumulate material in this horizon range from meters across to a few crystals across, and characteristically have cusped margins with the enclosing fine-grained gabbro-norite. The enclosing fine-grained material exhibits fluidal textures wrapping around the plagioclase cumulate inclusions. In other places, fine-grained material infiltrates the coarser cumulates in wispy screens. Lastly, at the bottom and top of the section there are several places where a (relatively thin) fine-grained layer wedges out within an outcrop. The simplest explanation for these relationships is that the fine-grained material was intruded into the cumulate layers, after the latter had formed, but while they were still hot, and perhaps even while they were still partially molten themselves. Contacts between the fine-grained rocks and their host can be very sharp, but are never chilled.

Petrographically, the fine-grained gabbro-norite layers can be either porphyritic, with plagioclase as the only phenocryst mineral, or nearly aphyric. In the thickest of the fine-grained layers, which are most easily correlated along strike from outcrop to outcrop, this characteristic (porphyritic vs. aphyric) is consistent within a given layer along strike. The plagioclase phenocrysts vary in size with their mesostasis: those in the very finest-grained layers are smaller than the phenocrysts in the somewhat coarser-grained layers. The mesostasis of the fine grained layers commonly exhibits fluidal textures around phenocrysts and larger cumulate inclusions, but in the absence of inclusions shows a planar foliation parallel to the contacts of the layer.

The cumulate layers vary from relatively massive, medium-coarse gabbro-norite to very leucocratic anorthosite. Some of the cumulate layers are internally quite variable in their plagioclase/pyroxene ratio. The anorthosite, whether leucocratic zones within a cumulate layer, or a layer that is entirely leucocratic, consists of coarse blocky plagioclase, and usually have at least some coarse interstitial (transitioning to oikocrystic) magnetite. The uppermost unit exposed in this area west of the Boulder River, a very leucocratic anorthosite, also contains coarse inter-

stitial apatite.

Although the rocks show great variety in their field relations and overall petrography, they are chemically monotonous. Most are gabbronoritic, that is, they have subequal amounts of normative Hy and Di, regardless of how much total pyroxene is in the rock. Table 1 shows average bulk compositions and gross normative mineral compositions for the four main rock types: the fine-grained (intrusive) gabbronorite, the coarse-grained (cumulate) gabbronorite, the magnetite-free anorthosite, and the magnetite-bearing anorthosite.

Normative An contents for the nine individual samples of fine-grained gabbronorite range from An62 to An68 mol percent; the cumulate gabbronorite samples have An62 to An66 mol percent, the five magnetite-free anorthosite samples have An61 to An63 mol percent, and the three magnetite-bearing anorthosites range from An62 to An64. The anorthosite samples are higher in K<sub>2</sub>O than the gabbronorites, with the magnetite-bearing anorthosites being higher than the magnetite-free anorthosites.

Ranges in calculated (Mg/Mg+Fe) mol ratios in the normative mafic minerals are

complicated by the need to assume a ferric/ferrous ratio. Because most of these rocks contain no magnetite or other ferric iron-bearing phase, we have assumed that the original Fe<sub>2</sub>O<sub>3</sub> content of most samples was effectively zero. This is compatible with the generally reduced character of the Stillwater Complex, and the local occurrence of graphite as an accessory phase, as reported in Mathez and others (1989). For the fine-grained gabbronorite, Mg/Mg+Fe ranges from 0.65-0.70, with an identical range (0.66-0.70) for the coarse-grained gabbronorite. The normative mafic silicates in the magnetite-free anorthosite are consistently somewhat more iron-rich (0.59-0.63). The presence of magnetite in several anorthosite samples means that Fe<sub>2</sub>O<sub>3</sub> of those samples cannot be zero; for these three, we have calculated the norms of the rock using the observed ferric/ferrous ratios. The resulting Mg/Mg+Fe values (0.52, 0.57 and 0.78) show that in general the mafic silicates in the magnetite-bearing anorthosite are more iron-rich than those the other anorthosites, even when magnetite is calculated. TiO<sub>2</sub> contents of the magnetite-bearing anorthosites are also higher, consistent with the presence of titanomagnetite.

**Table 1.** Average compositions of major rock types from the Boulder River outcrops (renormalized dry weight).

	1	2	3	4
SiO <sub>2</sub>	52.14	52.29	52.51	52.50
TiO <sub>2</sub>	0.16	0.21	0.22	0.32
Al <sub>2</sub> O <sub>3</sub>	17.23	17.80	22.48	25.23
Fe <sub>2</sub> O <sub>3</sub>	1.31	1.32	1.23	1.50
FeO	5.95	5.21	3.57	2.51
MnO	0.15	0.12	0.10	0.07
MgO	8.26	7.61	4.18	1.95
CaO	12.37	12.83	12.30	12.15
Na <sub>2</sub> O	2.21	2.41	3.14	3.42
K <sub>2</sub> O	0.08	0.11	0.18	0.26
P <sub>2</sub> O <sub>5</sub>	0.00	0.00	0.00	0.00
CO <sub>2</sub>	0.11	0.07	0.06	0.04
S	0.01	0.00	0.00	0.02
SUM	99.99	99.98	99.99	99.97
(Mg/Mg+Fe) in silicates, mol percent	67.4	68.2	61.9	68.5
Fe <sub>2</sub> O <sub>3</sub> assumed	nil	nil	nil	as analyzed
An content plagioclase, mol percent	65.0	63.4	62.4	63.2

Notes: Col. 1: Average of 9 fine-grained intrusive gabbronorites Col. 2: Average of 10 coarse-grained cumulate gabbro-  
norites Col. 3: Average of 5 magnetite-free cumulate anorthosites Col. 4: Average of 3 magnetite-bearing cumulate  
anorthosites

In comparing the Boulder River occurrence of fine-grained intrusive gabbro-norite with the Picket Pin outcrops, we note the following differences: (1) The mafic minerals in the Boulder River rocks are mostly altered, while the Picket Pin rocks are fresher. (2) The outcrops are more continuous, and offer a more extensive section, and somewhat better view of the relationships between the fine-grained gabbro-norites and the cumulates, than can be obtained from the frost-shattered outcrops along the ridge at Picket Pin. (3) The cross-cutting Na- and K-rich pegmatoids that are pervasively present at Picket Pin are completely absent in the Boulder River area. This suggests that the pegmatoids are not intrinsically part of the stratigraphy of the Stillwater Complex, but may be associated with a later alaskite body that intruded the Stillwater east of the Picket Pin area.

The significance of this package of fine-grained rocks is still somewhat enigmatic. The field relations clearly support the idea that the fine-grained noncumulate rocks have invaded and locally disrupted pre-existing cumulates. However, the fine-grained rocks are not chilled against the cumulates, but locally infiltrate them for some distance, as though the thermal contrast between them and the cumulates was not great. From the chemical data presented here it is clear that any compositional contrast that may have initially

existed between the invading material and the cumulates has been obliterated during subsequent slow cooling, with out-migration of residual liquid. However, the fine-grained layers are not themselves residual in composition, relative to the cumulates, so cannot be internally generated, auto-intrusive bodies analogous to aplites in granites: they must represent material added to the body of the Complex. The fact that the fine grain size and local porphyritic texture of the intrusive gabbro-norite have been preserved argues that either (1) the Stillwater magma chamber was near the end of its life or (2) these rocks are near enough to the margin of the body, so that the textural contrasts were not destroyed by annealing.

### References

- Carlson, R. R. and Zientek, M. L., 1985, Guide to the Picket Pin Mountain Area, In The Stillwater Complex, Montana: Geology and Guide, Montana Bureau of Mines Special Publication 92, p. 262-276.
- 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*, v. 30, p. 153-173.