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A review of some features potentially indicative of the presence of platinoid mineralization as deduced from the Stillwater Complex, Montana (USA)

A.H. van der Veen
Billiton Research b.v. Westervoortse dijk 67d 6800 AA, Arnhem, The Netherlands (Present address: Instituut voor Aardwetenschappen, Budapestlaan 4, 3584 CD Utrecht, The Netherlands)

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Abstract

The Stillwater Complex of South Montana is a layered differentiated ultramafic intrusive body of late Archaean age. It crops out along strike over 48 km and contains one of the richest zones of platinum group elements (PGE) in the world – the JOHNS-MANVILLE Reef. This reef is almost two metres thick and consists of 0.5 to 2.0% sulfide enclosed in noritic rocks. The sulfides are principally pentlandite, pyrrhotite and chalcopyrite with locally minor pyrite. Minerals of the braggite-vysotskite series contain the bulk of the platinum group elements. A relatively high Ni/Cu ratio of 1.3, and extremely high – 32 g/ton – concentration of platinum and palladium, a (Pt + Pd)/(Os + Ir + Ru) ratio of 230 and a high magma/sulfide or R ratio are quite different from what may be expected from sequential differentiation and crystal settling in an ultrabasic magma chamber. The most acceptable genetic model for the chemistry and geometry is one suggesting turbulent injection of a second buoyant magma into the original magma chamber to so alter the magma/sulfur ratios that the observed metal abundances and ratios are reached.

A number of the petrological and geochemical features of the Stillwater Complex, and particularly their geometrical distributions are of significance for the understanding of such complexes and can be used in exploration. Some of these can be summarized as follows:

If in a sulfide zone, 400–1000 m above the first appearance of cumulus plagioclase, one finds

- the presence of chromitite layers,
- that olivine is the cumulus mineral in addition to plagioclase,
- the presence of 'pegmatoid' zones (i.e. distinct orthocumulate texture),
- that there is evidence of magma injection (slump textures etc.),
- that the Ni/Cu ratio is greater than 1,
- that there is no apparent nickel depletion of the associated reef olivine,
- and that rare earth element abundances and ratios of plagioclase change in a way suggesting magma replenishment,

then it is highly probable that such a sulfide zone has an economically interesting platinoid content.

Introduction

In July 1985, during the Magmatic Sulfide Conference IV (sponsored by IGCP – IUGS, project group 161 – and by UNESCO) the Stillwater Complex in Montana was visited. This layered mafic-ultramafic intrusive body hosts a stratiform deposit, the JOHNS-MANVILLE (Howland) or J-M Reef, which contains sulfides that are rich in platinum group elements (PGE).

The aim of this article is to review some important indications of PGE mineralization which are

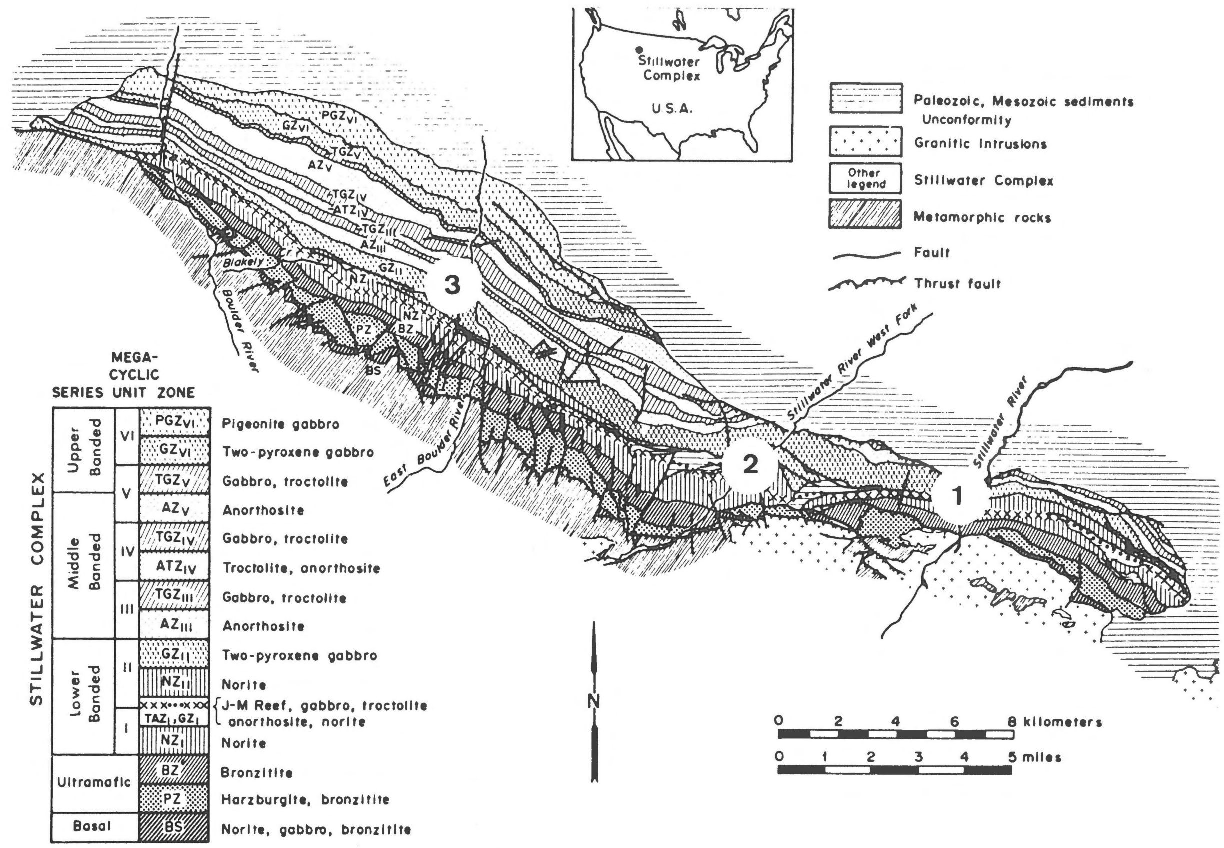

Fig. 1. Geologic map of the Stillwater Complex, showing the location of the J-M Reef, the Minneapolis Adit (1), West Fork (2) and Frog Pond (3) areas. The stratigraphy is that of Todd et al. (1982), with modification of Ultramafic series terminology for consistency with this paper (adapted from Czamanske & Zientek, 1985).

of genetic significance and which also can be used in exploration.

Geological setting

The Stillwater Complex is a differentiated stratiform mafic and ultramafic intrusive body of late Archaean age: 2701 ± 8 Ma (DePaolo & Wasserburg, 1979). It is exposed in Stillwater, Sweet Grass- and Park Counties, Montana, for about 48 km along the northern margin of the Beartooth Mountains. Intrusive contacts with folded metasedimentary rocks are visible in the west and locally in the east, where the complex is intruded by late Archaean quartz monzonite plutons. The complex is only partly exposed and its entire original size and shape are unknown. Prior to emplacement, the metasediments were isoclinally folded and then refolded in broad warps along NW plunging axes. Before or during emplacement the sediments may have been subject to low-grade metamorphosis. Subsequently, the rocks were intruded by the Stillwater magma, which cooled and crystallized in a non-orogenic environment, demonstrated by continuously traceable thin cumulate layers (Fig. 1). In eastern exposures the complex cuts out some of the stratigraphy that is recognized in exposures of hornfels farther to the west. This relationship may imply emplacement along a fault zone or along an unconformity, although in certain other areas the protolith of the hornfels plays an important role in controlling the position of the intrusive contacts.

Lithologies

Sufficient fieldwork has not yet been done to propose the ultimate stratigraphic subdivision of the Stillwater Complex. Figure 2 (after Czamanske & Zientek (1985)) represents therefore a first attempt to reach a consensus among several different schemes that have been proposed. There are three major units in the generally concordant layered mafic and ultramafic intrusive (Lambert & Simmons (1983)):

a) a Basal series, 30–70 m thick consisting of bronzite-plagioclase cumulates, some of which are fine grained (chilled?), some are cumulates, and others are contaminated with country rock (Page, 1979);
b) an Ultramafic series, further divided into (1) a lower Peridotite member 610 m thick, consisting, of cyclic olivine cumulates, chromite cumulates, olivine-bronzite cumulates and bronzite cumulates and (2) an upper Bronzitite member 366 m thick, consisting, of bronzite cumulates;
c) a Banded series, which is the upper zone, consisting of a about 4.5 km thick sequence of plagioclase – bronzite cumulates, plagioclase-bronzite augite cumulates, plagioclase cumulates and minor plagioclase – olivine cumulates.

The top of the Ultramafic series and the base of the Banded series is marked by the first appearance of cumulus plagioclase. The Banded series is subdivided into three subseries: Lower, Middle, Upper. The PGE-bearing J-M Reef occurs in the Lower Banded series and, more precisely, in the Olivine-bearing zone 1 (OBZ1), (see arrow in Fig. 2).

Petrological setting of the J-M Reef

The J-M Reef occurs in the Olivine-bearing zone 1 (OBZ1), which lies between Gabbronorite I and II. It is situated about 400 m above the top of the Ultramafic series. The most distinctive feature of OBZ1 is the reappearance of olivine as a cumulus phase. The reef is a semicontinuous layer extending over the entire strike length of the complex.

It is approximately 2 m thick, consisting of 0.5 to 2% disseminated sulfides within troctolite, anorthosite and norite. In Minneapolis adit area sulfides are associated with the first appearance of olivine in OBZ1, in contrast to the situation in the West Fork (see Fig. 3) and Frog Pond areas where the reef is associated with the fifth olivine cumulate layer. This represents a primary transgression in the OBZ1 stratigraphy, with the lower olivine cumulate layers pinching out to the east. Sulfides may occur higher in the section at the eastern end of the adit, although the situation is greatly complicated by faulting (Bow et al. 1982).

At the eastern end of the adit area, the sulfides of the reef occur within olivine-rich rocks – either in layers of olivine cumulate with intercumulus plagioclase and pyroxene oikokrysts, or in an unusual heterogeneous rock type referred to as 'mixed rock' (irregular masses or 'boulders' of olivine-rich rocks – within a matrix of anorthosite (Bow et al. 1982)). The sulfides occur as disseminated interstitial blebs.

From east to west, over approximately 700 m of strike, olivine becomes progressively more resorbed and replaced by large oikocrysts of bronzite and the rock changes progressively towards a norite.

Sulfide silicate textures indicate that sulfide (as at the eastern end) was present as a cumulus phase and that olivine resorption must have occurred at a stage when the sulfide blebs were at least partially solid with a temperature less than about 1100° C (Barnes & Naldrett, 1985).

Composition of the J-M Reef sulfides

The sulfide blebs consist principally of pentlandite, pyrrhotite, and chalcopyrite, the typical mineralogy of a magmatic sulfide assemblage. Pyrite is a common minor constituent, particularly in the bronzite-rich, olivine-poor rocks. Platinum and palladium occur predominantly as sulfides of the braggite-vysotskite series and as a wide variety of Te-, As-, Bi-, and Sn-bearing phases (Todd et al., 1982). Millerite, violarite, mackinawite, and marcasite occur in serpentinized samples. Barnes & Naldrett (1985) examined the average composition of the sulfide fraction of the reef in 40 rock samples:

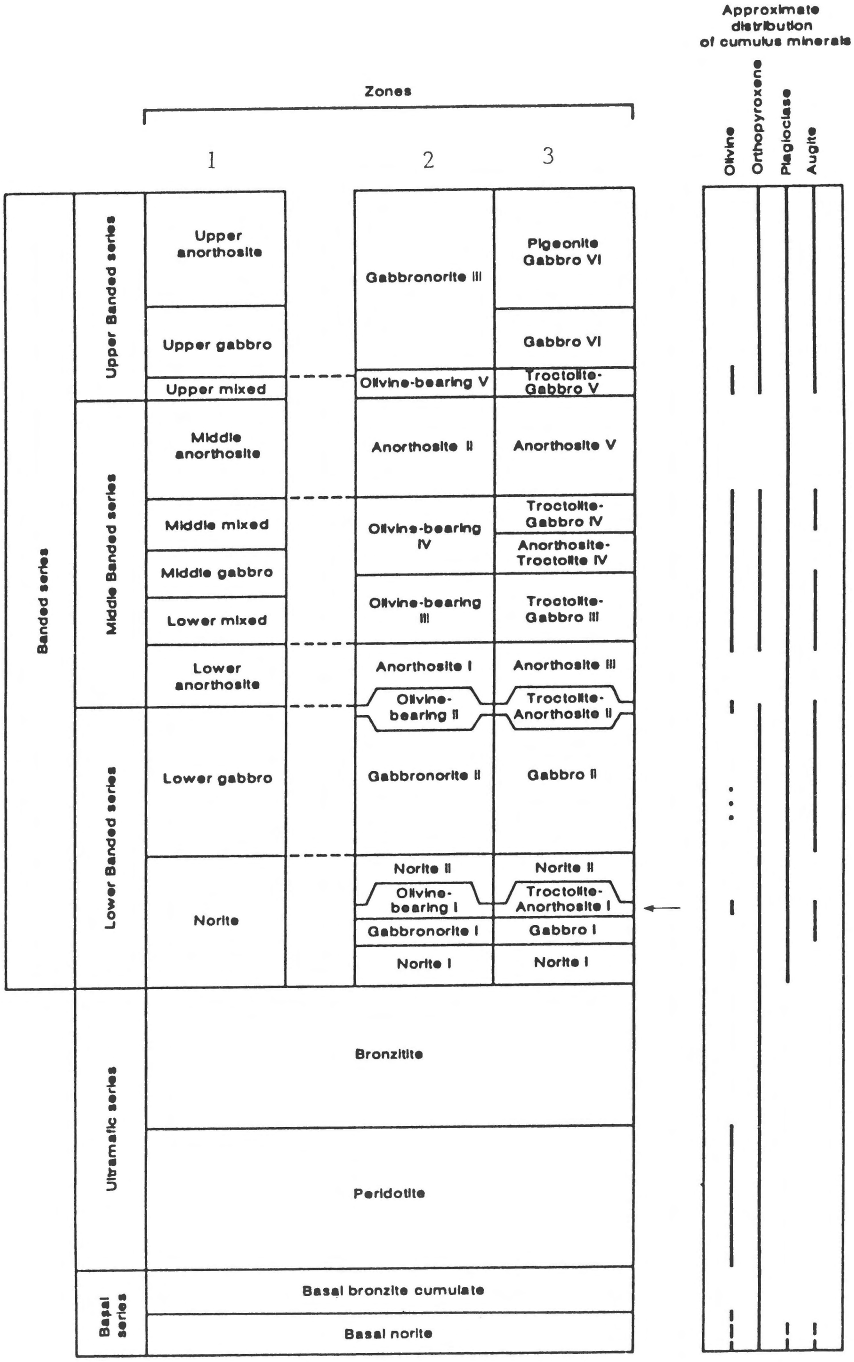

Fig. 2. Subdivisions of Stillwater stratigraphy as used in this article and approximate stratigraphic distribution of cumulus minerals (adapted from Czamanske & Zientek, 1985). Because the ultimate stratigraphic subdivision of the complex cannot yet be established this represents the first attempt to reach some consensus among several different schemes that have been proposed. Stratigraphy 1 is of Segerstrom & Carlson (1982), nr. 2 is of McGallum et al. (1980) and nr. 3 is of Todd et al. (1982). (J-M Reef indicated by an arrow.)

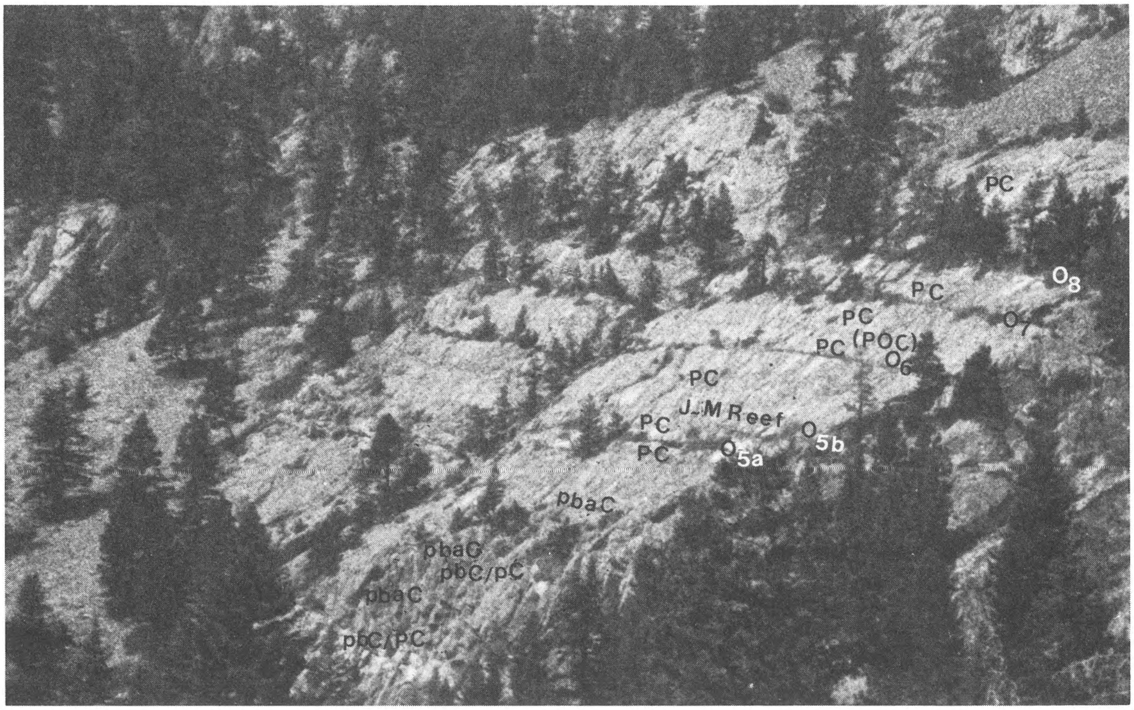

Fig. 3. West Fork Cliff's exposure, West Fork of the Stillwater River, at approximately 7,000 feet elevation and 300 m west of the J-M exploration adit. Note the conspicuous layering in the TAZ 1 layer accentuated by bands of vegetation which are best developed on members O7, O8, and to a lesser extent, O5a, O5b, and O6. The J-M Reef shows a darker, concave surface which is overlain by a thick pC unit and is underlain by the O5a and O5b marker layers and a footwall anorthosite. Several shallow rock trenches blasted across the PGE zone provide fresh exposures for sampling. The dark and light vertical banding is caused by growth of lichens and other weathering features on the smooth rock surface.

olivine cumulates (15), mixed rock (17), plagioclase bronzite cumulates (11). Normalized to 100% sulfide and calculated for 35% (m/m) S in bulk sulfide, the sulfides in the Minneapolis adit area contain 9.3% Ni; 6.9% Cu and 0.7% PGE (1560 μg/g Pt, 5540 μg/g Pd). The gold contents of he rocks are highly irregular; average 200 μg/g ± 290 for one standard deviation. The strongly coherent behaviour of the PGE elements, nickel, copper and sulfur indicates that all these elements are held dominantly in the sulfide fraction of the reef and that the major control on grade is sulfide abundance. There is little variation in bulk sulfide composition between samples. However, a plot of nickel versus sulfur does allow identification of a group of rocks, rich in olivine, in which the nickel contents are proportionally high for a given sulfur content.

The most striking feature of the composition of the J-M Reef sulfides is their extremely high concentration of platinum and palladium compared with all other known magmatic sulfide deposits except the UG-2 chromitite of the Bushveld Complex, South Africa (McLaren & de Villiers, 1982). Even the most prolific of the world's producers – The Merensky Reef –, South Africa is not as rich! The PGE content of the sulfides of the J-M Reef is about 14 times higher: the palladium content 42 times higher and the platinum content about 5 times higher than that of the sulfides of the Merensky Reef. The nickel and copper contents are about the same as those of the Merensky Reef or other Ni/Cu dominant deposits (Barnes & Naldrett, 1985). Equally exceptional is an unusually high (Pt + Pd)/(Os + Ir + Ru) ratio of about 230 for the J-M Reef, compared with 9.5 for the Merensky Reef, 10 for the Norils'k, USSR and the Ungava, USA deposits, and 10 to 25 for sulfides associated with other gabbroic intrusions: Sudbury, Canada, Duluth, USA and Insizwa, Southern Africa (Naldrett, 1981).

The platinum-palladium content of the J-M Reef is estimated to average 32 g/ton (Financial Times Sept., 17, 1985) whereas the total PGE contents of the Merensky Reef and the UG-2 chromitite layer are only 8 g/ton (Campbell et al., 1983).

Genetic considerations

It is beyond the scope of this paper to undertake an exhaustive review of the genetic models that have been proposed to explain the PGE mineralization at Stillwater. However, a view of the origin of this exceptional deposit will inevitably influence exploration concepts applied to PGE exploration worldwide. In particular, an explanation of why the J-M Reef sulfides are so rich in platinoids and have such high (Pt + Pd)/(Os + Ir + Ru) ratios may help identify equivalent situations elsewhere.

By analogy with models suggested for other systems the obvious hypothesis is one involving extreme fractionation of a PGE-rich silicate magma from which PGE-bearing sulfides exsolve and settle out to form the reef (e.g. Irvine et al., 1983). The main problem with this hypothesis is that the normal consequence of such a fractionation mechanism is marked enrichment of copper over nickel. The relatively high Ni/Cu ratio (1.3) in the J-M Reef is a strong indicator that it was not formed by any commonly accepted differentiation mechanism acting on an unusually PGE-rich magma.

Nickel-copper deposits are normally low in PGE owing to: (1) the presence of low magma/sulfur ratios (R), (2) the rapid segregation of sulfide, and (3) the incomplete equilibration of sulfide with the silicate magma during the early stages of fractionation when such deposits normally form (Campbell & Barnes, 1984). Thus, a mechanism is required to raise the value of (R). Barnes & Naldrett (1985) suggested high values of (R) could arise from a process of efficient magma mixing during turbulent injection of a buoyant replenishing magma into the Stillwater magma chamber. This would enable wide dispersion of sulfide droplets through a large body of magma and enhance the opportunity for equilibration of the two liquids. Sulfide and contemporaneous olivine would form first in a layer of hybrid magma and then settle through the underlying, more iron-rich liquid to accumulate into the crystal pile. As a consequence, and despite lateral variations in rock type, the resultant reef would have a high degree of compositional uniformity in copper, nickel and platinoids. Any lateral variations in the non-sulfide fraction could be due to variations in the composition of the mixing magmas or changes in the degree of mixing or both. Equilibration between olivine and sulfide in the J-M Reef is restricted to the reef itself and occurs on the scale of individual grains. This explains the highly fluctuating nickel contents of the olivines. The olivine compositions have therefore been buffered by the associated sulfides, despite the high olivine/sulfide ratios in the reef.

Exploration criteria

A number of petrological, geochemical and spatial features are of exploration significance (Campbell et al., 1983):

1. PGE are closely tied to sulfide;
2. The magma/sulfide ratio needed for formation of a platiniferous reef is most likely to occur 400 to 1000 m above the first appearance of plagioclase as a cumulus phase;
3. Thick chromitite layers indicate high magma/sulfide ratios and associated sulfides have a high probability of being platiniferous;
4. In the Stillwater Complex PGE mineralization is closely associated with a mixed package of olivine-bearing cumulates, intercalated between layered gabbroic and noritic cumulates of the Lower Banded Zone. The most distinctive feature in the J-M Reef is the reappearance of olivine, and elsewhere chromite ± olivine as cumulus phase. At one site the PGE mineralization is associated with the first olivine cumulate or mixed rock layer and elsewhere with the fourth or fifth olivine-bearing layer. The loca-

tion of the mineralization depends at what stage in the liquid mixing process the sulfur fugacity is high enough to precipitate sulfide;

5. PGE mineralization is associated with pegmatoid layers at or near the base of cyclic (macro-rhytmic) layers. These pegmatoids have a distinct orthocumulate texture. Orthocumulates* are true gravity cumulates with a high initial porosity (50–60%). Normal cumulates, formed by in situ crystallization have lower initial porosity (5–20%). As a consequence, orthocumulates have a lower intercumulus solidus temperature and act as traps for volatiles and, to a lesser extent for incompatible elements that are expelled during solidification of cumulates that formed with lower initial porosity (Campbell et al., 1983).
6. The site of PGE-rich sulfides is intimately linked to a process of multiple injection and mixing of geochemically distinct magmas (Lambert & Simmons, 1983). Such injections which cause major disturbances in the magma chamber at the time that the olivine-rich zone was formed may be visible in the field, e.g. as slump structures near the top of Gabbro Norite Zone I (Todd et al., 1979). The addition of a fundamentally different magma type to the magma chamber at the time that the reef was formed is also confirmed by the crystallization sequence: plagioclase crystallizing before bronzite in the associated plagioclase-rich rocks. This is different from that observed in the Ultramafic series at lower levels in the complex.
7. A relatively high Ni/Cu ratio (>1) of the sulfide suggests a high R factor and is a must for rich PGE mineralization to occur. The reef olivines are not depleted in nickel as indicated by plotting the NiO/Fo contents and comparing these with he field of layered intrusion olivines from Simkin & Smith (1970). Moreover, outside the reef,the within-sample scatter of nickel in olivine is in all cases less than 200 µg/g, whereas nickel contents in reef olivines fluctuate between 300–600 µg/g even within a single thin section between olivine grains and sulfide blebs (Barnes & Naldrett, 1985).
8. At Stillwater the rare earth element (REE) abundances and ratios change dramatically as the olivine-bearing layer at the base of the PGE-bearing reef is crossed with a decrease in abundance of overall REE and change in REE ratios. REE contents in the cumulus plagioclase from a stratigraphic sequence representing the crystallization product of a single magma are normally continuously enriched upwards. However, the behaviour of REE in cumulus plagioclase at Stillwater is better explained by addition of a new magma which mixed with the highly evolved residual magma. Also, it provides conclusive evidence that the reappearance of magnesium-rich olivine as a cumulus phase is not due to externally induced pressure fluctuations acting in a single evolving magma (Lambert & Simmons, 1983).

* An ortho- or true cumulate is composed chiefly of one or more cumulus minerals plus the crystallization products of the intercumulus liquid. It is formed by gravity settling of the cumulus minerals. Normal cumulates are formed by in situ crystallization, controlled by the balance between nucleation and crystal growth at the crystal-liquid interface (Campbell, 1978).

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References

Barnes, S.J. & A.J. Naldrett 1985 Geochemistry of the J-M (Howland) Reef of the Stillwater Complex, Minneapolis Adit Area. I. Sulfide chemistry and Sulfide-Olivine Equilibrium – Econ. Geol. 80: 627–645

Bow, C.S., D. Wolfgram, A. Turner, S.J. Barnes, J. Evans, M. Zdepski & A. Boudreau 1982 Investigations of the Rowland Reef of the Stillwater Complex, Montana: I. Stratigraphy and petrology – Econ. Geol. 77: 1481–1492

Campbell, I.H. 1978 Some problems with the cumulus theory – Lithos, 11: 311–323

Campbell, I.H., A.J. Naldrett & S.J. Barnes 1983 A model for the origin of the platinum-rich sulfide horizons in the Bushveld and Stillwater Complexes – J. Petrol. 24, 2: 133–165

Campbell, I.H. & S.J. Barnes 1984 A model for the geochemistry of the platinum group elements in magmatic sulfide deposits – Can. Mineral. 22: 151–160

Czamanske, G.K. & N.L. Zientek 1985 The Stillwater Complex, Montana: Geology and Guide – Mont. Bur. Mines Geol. Spec. Publ. 92: 396 pp

DePaolo, D.J. & G.J. Wasserburg 1979 Sm-Nd age of the Stillwater Complex and the mantle evolution curve for neodymium – Geochim. Cosmochim. Acta, 43: 999–1008

Irvine, T.N., D.W. Keith & S.G. Todd 1983 The J-M platinum-palladium Reef of the Stillwater Complex, Montana: II. Origin by double-diffuse convective magma mixing and complications for the Bushveld Complex – Econ. Geol. 78: 1287–1334

Lambert, D.D. & E.C. Simmons 1983 Platinum-group element ore-forming process in mafic layered intrusions. Geochemical evidence from the Stillwater Complex, Montana – Min. Eng.: 1291–1298

McCallum, I.S., L.D. Raedeke & E.A. Mathez 1980 Investigations of the Stillwater Complex: Part 1. Stratigraphy and structure of the Banded zone. In: Irving, A.J. & M.A. Dungan (eds.): The Jackson Volume – Am. J. Sci. 280-A: 59–87

McLaren, C.H. & J.P.R. De Villiers 1982 The platinum group chemistry and mineralogy of the Bushveld Complex – Econ. Geol. 77: 1348–1366

Naldrett, A.J. 1981 Nickel sulfide deposits: Classification, composition, and genesis – Econ. Geol. 75th anniv. vol.: 628–685

Page, N.J. 1979 Stillwater Complex, Montana – Structure, mineralogy and petrology of the Basal zone with emphasis on the occurrence of sulfides: U.S. Geol. Surv. Prof. Pap. 1038: 69 pp

Segerstrom, K. & R.R. Carlson 1980 Preliminary geologic map of the eastern end of the upper zones of the Stillwater Complex, Stillwater County, Montana – U.S. Geol. Surv. Open-file Rep. 80–364, 1 sheet, 1:62,500

Simkin, T. & J.V. Smith 1970 Minor element distribution in olivine – J. Geol. 78: 304–325

Todd, S.G., D.J. Schissel & T.N. Irvine 1979 Lithostratigraphic variations associated with the platinum-rich zone of the Stillwater Complex – Carnegie Inst. Washington Yearbook 78: 461–467

Todd, S.G., D.W. Keith, L.W. Leroy, D.J. Schissel, E.L. Maun & T.N. Irvine 1982 The J-M platinum-palladium Reef of the Stillwater Complex, Montana: I. Stratigraphy and petrology – Econ. Geol. 80: 1454–1480