

PROGRAM AND ABSTRACTS

FOURTH INTERNATIONAL PLATINUM SYMPOSIUM

UNIVERSITY OF TORONTO
AUGUST 2-4, 1985

MAGMATIC SULFIDE FIELD CONFERENCE IV

KETCHIKAN, ALASKA AND STILLWATER, MONTANA
JULY 14-31, 1985

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PROGRAM

FOURTH INTERNATIONAL PLATINUM SYMPOSIUM, TORONTO

Lectures are held in Room 2158, Medical Sciences Building, University of Toronto.

Friday Morning, August 2, 1985

0845-0900 A. J. Naldrett

Welcome and opening remarks

PGE AND PGM IN THE STILLWATER COMPLEX CHAIRPERSON: N. J. PAGE

0900-0920 M. L. Zientec*, L. Mei

Platinum-group-element concentrations in rocks near the base of the Stillwater Complex, Montana

0920-0940 A. Volborth*, E. F. Stumpfl,
M. Tarkian, R. M. Housley

Examples of Pd-Pt mineralization along the 35-km strike of the Stillwater Reef, Montana

0940-1000 L. D. Raedeke*, R. W. Vian

A three-dimensional view of mineralization in the Stillwater J-M Reef

1000-1020

Coffee Break

CHAIRPERSON: E. F. STUMPFL

1020-1040 A. E. Boudreau*, I. S. McCallum

The Picket Pin Pt-Pd deposit, Stillwater Complex, Montana

1040-1100 E. A. Mathez*, A. E. Boudreau,
I. S. McCallum

Apatite and biotite from the Stillwater and Bushveld Complexes and the nature of hydrothermal activity

1100-1120 A. E. Boudreau*, I. S. McCallum

Evidence for mineral reactions and metasomatism by silica-undersaturated Cl-rich fluids in the Main Pt-Pd zone, Stillwater Complex, Montana

1120-1140 R. W. Talkington*, B. R. Lipin

Platinum-group-element-bearing inclusions in chromite of the ultramafic zone, Stillwater Complex, Montana: occurrence, chemistry, and petrological significance

1140-1200 J. Parks*, R. E. T. Hill

Phase compositions and cryptic variation in a 2.2-km section of the Windimurra layered gabbroic intrusion, Yilgarn block, Western Australia: a comparison with the Stillwater Complex

Friday Afternoon, August 2, 1985

PGE AND PGM IN LAYERED AND OTHER ULTRAMAFIC-MAFIC INTRUSIONS CHAIRPERSON: R. A. ALCOCK

1330-1350 H. T. Papunen

PGE in Svecokarelian nickel-copper occurrences, Finland

1350-1410 T. Alapieti*, J. Lahtinen

Stratigraphy, petrology and PGE mineralization in the Early Proterozoic Penikat layered intrusion, northern Finland

*Speaker.

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|-----------|---|---|
| 1410-1430 | F. Gray*, N. J. Page,
S. A. Wilson, R. R. Carlson | Contrasting petrology and PGE geochemistry of zoned ultramafic complexes, Klamath Mountains, California and Oregon |
| 1430-1450 | A. V. Brown*, N. J. Page,
A. H. Love | Platinum-group-element geochemistry of the Serpentine Hill Complex, Dundas Trough, Western Tasmania |
| 1450-1510 | R. F. J. Scoates*,
O. R. Eckstrand | Potential for platinum-group elements in the Fox River Sill, northeastern Manitoba |
| 1510-1530 | D. Ohnenstetter*,
D. H. Watkinson, R. W. Talkington | Cryptic compositional variation in laurite and enclosing chromite from the Bird River Sill, Manitoba |
| 1530-1600 | Coffee Break | |
| | CHAIRPERSON: M. PRENDERGAST | |
| 1600-1620 | E. Çogulu | Platinum-group elements and variations in chromian spinel in the Crystal Lake Gabbro, Thunder Bay, Ontario |
| 1620-1640 | H. C. H. Dillon-Leitch*,
D. H. Watkinson, C. J. A. Coats | Variation in platinum-group-mineral distribution and composition from the Proterozoic Donaldson West Ni-Cu deposit, northern Quebec |
| 1640-1700 | W. F. Rowell, A. D. Edgar* | Genesis of platinum-group elements and gold in a hydrothermal sulfide occurrence in a Nipissing intrusion, northeastern Ontario |
| 1700-1720 | G. Garuti*, R. Rinaldi | Mineralogy of melonite-group PGM and other tellurides from the Ivrea-Verbano basic complex, Western Italian Alps |
| 1720-1740 | J. Hak, D. H. Watkinson*,
I. R. Jonasson | New microprobe data on platinum-group minerals and their relationships to metamorphism and deformation of host Ni-Cu sulfide deposits |
| 1740-1800 | L. B. Cochrane*, A. E. Beswick | Geochemical relationships in the South Range of the Sudbury Igneous Complex |

Friday Evening, August 2, 1985

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| 1930 | Symposium dinner, Faculty Club, University of Toronto |
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Saturday Morning, August 3, 1985

PGE AND PGM IN ULTRAMAFIC-MAFIC FLOWS AND OPHIOLITES

CHAIRPERSON: M. R. SHARPE

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| 0830-0850 | S.-J. Barnes*, A. J. Naldrett | The fractionation of the platinum-group elements at the Alexo komatiite, Abitibi greenstone belt, northern Ontario |
| 0850-0910 | M. Tredoux*, J. P. F. Sellschop,
G. Davies, M. J. DeWit | The behavior of the PGE and Au during partial melting and fractional crystallization: evidence from magmas on the Kaapvaal craton |
| 0910-0930 | J. H. Crocket*, W. E. MacRae | PGE distribution in komatiitic and tholeiitic volcanic rocks from Munro Township, Ontario |

*Speaker.

- 0930-0950 G. E. Brügmann*, N. T. Arndt,
A. W. Hofmann, H.-J. Tobschall
Precious-metal abundances in komatiites and
komatiitic basalts: implications for the genesis of
PGE-bearing magmatic sulfide deposits
- 0950-1010 D. R. Hudson
Platinum-group minerals from the Kambalda
nickel deposits, Western Australia
- 1010-1030 A. Cowden*, M. J. Donaldson,
A. J. Naldrett, I. H. Campbell
Platinum-group elements in the komatiite-hosted
Fe-Ni-Cu sulfide deposits at Kambalda, Western
Australia
- 1030-1050 Coffee Break

CHAIRPERSON: J. H. CROCKET

- 1050-1110 M. Tredoux*, R. J. Hart,
J. P. F. Sellschop,
M. J. DeWit, R. A. Armstrong
PGE in the ~ 3.6-Ga Bon Accord Ni-Fe-Co-Cr
occurrence, Barberton, South Africa: implications
for crust-mantle-core segregation
- 1110-1130 N. J. Page*, D. A. Singer
C. A. Carlson, B. C. Moring,
J. M. McDade, S. A. Wilson
Platinum-group-element resources in podiform
chromite from California and Oregon
- 1130-1150 H. M. Prichard*, P. J. Potts,
C. R. Neary
Platinum-group minerals in ophiolite complexes:
an example from Shetland
- 1150-1210 D. Rammlmair, T. W. Weiser*
Stratigraphic relations of the PGE mineralization
in the Central Palawan Complex, Philippines
- 1210-1230 P. J. Whittaker*,
D. H. Watkinson
Platinum-group minerals from chromitite in alpine-
type peridotite of the Cache Creek Group, British
Columbia

Saturday Afternoon, August 3, 1985

THE BUSHVELD IGNEOUS COMPLEX
CHAIRPERSON: G. VON GRUENEWALDT

- 1330-1350 C. A. Lee*, M. Tredoux
PGE abundances in the Lower and lower Critical
Zones of the eastern Bushveld complex
- 1350-1410 M. R. Sharpe*, C. A. Lee,
M. Tredoux
Precious-metal and rare-earth concentrations of
Bushveld peridotite sills: indicators of magmatic
PGE contents
- 1410-1430 F. J. Kruger*, A. A. Mitchell
Discontinuities and variations of Sr-isotope sys-
tematics in the Main Zone of the Bushveld Com-
plex, and their relevance to PGE mineralization
- 1430-1450 I. H. Campbell
A fluid-dynamic model for the Merensky Reef
potholes
- 1450-1510 M. R. Sharpe
Sr and Nd isotope evidence for preserved density
stratification in the Main Zone of the Bushveld
Complex: implications for the origin of the
Merensky Reef and undiscovered PGE minerali-
zation in the Upper Zone
- 1510-1530 A. J. Naldrett*, C. Gasparriani,
S. J. Barnes, M. R. Sharpe,
G. von Gruenewaldt
The origin of the Merensky Reef

*Speaker.

1530-1600

Coffee Break

CHAIRPERSON: A. J. NALDRETT

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| 1600-1620 | C. G. Ballhaus, E. F. Stumpfl* | Graphite, platinum and the C-O-H-S system |
| 1620-1640 | Z. Johan*, D. H. Watkinson | Significance of a fluid phase in platinum-group-element concentration: evidence from the Critical Zone, Bushveld Complex |
| 1640-1700 | C. G. Ballhaus*, E. F. Stumpfl | Fluid inclusions in Merensky and Bastard Reefs, western Bushveld Complex |
| 1700-1720 | G. von Gruenewaldt*,
C. J. Hatton, S. B. Gain | Platinum-chromitite association in the Bushveld Complex |
| 1720-1740 | H. V. Eales, I. M. Reynolds* | Cryptic variations within chromitites of the Upper Critical Zone, northwestern Bushveld Complex |
| 1740-1800 | R. G. Cawthorn*, J. R. Barton,
J. White, M. J. Viljoen | The role of contamination in the evolution of the Platreef of the Bushveld Complex |

Saturday Evening, August 3, 1985

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| 2000-2045 | G. C. Ulmer*, D. P. Gold | Pothole structures: underground television footage from four platinum mines |
| 2045-2105 | D. P. Gold*, P. Deines,
Y. Touyinhthiphonexay,
G. C. Ulmer, D. E. Grandstaff,
T. Buntin | The nature and significance of igneous "pothole" structures in some layered intrusive complexes |
| 2105-2200 | Discussion | |

Sunday Morning, August 4, 1985

EXPERIMENTAL, DIAGNOSTIC AND OTHER STUDIES OF PGE AND PGM

CHAIRPERSON: L. J. CABRI

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| 0900-0920 | E. Makovicky*, M. Makovicky,
J. Rose-Hansen | Experimental studies on the solubility and distribution of platinum-group elements in base-metal sulfides in platinum-group-mineral deposits |
| 0920-0940 | C. D. Doyle*, A. J. Naldrett | The solution of nickel oxide in mafic magmas: a simple model |
| 0940-1000 | S. Karup-Møller | The system Pd-Co-S at 1000, 800, 600 and 400°C |
| 1000-1020 | | Coffee Break |

CHAIRPERSON: E. MAKOVICKY

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| 1020-1040 | J. C. Rucklidge, G. C. Wilson*,
E. F. Stumpfl, C. G. Ballhaus | Analysis of Pt-associated graphite by accelerator mass spectrometry |
| 1040-1100 | J. F. W. Bowles | A consideration of the development of platinum-group minerals in laterite |
| 1100-1120 | P. Theyer | Platinum-group elements in the Bird River Sill |
| 1120-1140 | S. A. Hiemstra | The vertical distribution of platinum-group and chalcophile elements in the UG-2 reef. |

*Speaker.

ABSTRACTS

FOURTH INTERNATIONAL PLATINUM SYMPOSIUM, TORONTO

STRATIGRAPHY, PETROLOGY AND PGE MINERALIZATION IN THE EARLY PROTEROZOIC PENIKAT LAYERED INTRUSION, NORTHERN FINLAND

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The Penikat Layered Intrusion is part of a belt of Early Proterozoic layered intrusions 2 440 Ma in age that extends across northern Finland. It is 23 km long, and located between late Archean granitic rocks and Early Proterozoic supracrustal rocks. The Marginal Series, with a somewhat contaminated chilled margin, separates the Penikat Intrusion from the underlying basement complex. The Layered Series is highly heterogeneous. It is divided into five megacyclic units, I-V from bottom to top, every unit comprising an ultramafic lower part and a gabbroic upper part.

The most remarkable zones of PGE mineralization, UM-IV, AP and PV, are concentrated in cyclic unit IV. The UM-IV mineralization, which is about 1 m thick, is mostly associated with pyroxenitic rocks at the lower contact of the unit, whereas the AP zone (about 0.5 m thick) is associated with gabbro and spotted anorthosite in the middle part, and the PV zone (about 1 m thick), with leucogabbro and anorthosite very close to the upper contact.

The proportion of the different platinum-group elements is relatively constant in each mineralized zone. The PV mineralization represents the most platinum-rich variety and the AP the most palladium-rich one, the ratio of Pd to Pt being typically about 2 (sulfide-free type) and 1.5 (sulfide-bearing type) for the UM-IV, 3.5 for the AP and 0.7 for the PV mineralization.

According to the new classification of platinum-group-element deposits proposed by Cabri & Naldrett, the typically sulfide-free UM-IV mineralization can be included in the oxide-silicate association as a possible new type, whereas the AP and PV mineralization can be classified as a Merensky Reef type of sulfide association.

GRAPHITE, PLATINUM AND THE C-O-H-S SYSTEM

CHRISTIAN G. BALLHAUS AND EUGEN F. STUMPFL*

Institute of Mineralogy and Petrology, Mining University, A-8700 Leoben, Austria

Microscopic studies have revealed the widespread occurrence of graphite, not only in the platiniferous dunite pipes of the Eastern Bushveld (Stumpfl & Rucklidge 1982), but also in pegmatites of the Merensky environment, and in the Merensky Reef. Several morphological types of graphite occur in close association with amphiboles, phyllosilicates, sulfides and PGE. Microprobe analysis shows significant chlorine contents in hydrous silicates and graphite; accommodation of Cl in the latter is as intercalation compounds. The $\delta^{13}\text{C}$ in the graphite ranges from -19 ‰ to -21‰, suggesting contamination by a crustal source, probably sediments of the Transvaal System in the footwall of the Bushveld Complex.

After incorporation into mafic magmas, carbon forms an integral constituent first of a volatile-rich magma, and, on incipient cooling and dissociation, of a supercritical C-O-H-S-(Cl) phase with associated melt. The former buffers the melt with respect to $f(\text{O}_2)$ over a considerable part of its evolutionary path; the concomitant formation of graphite and hydrated silicates ($\pm$ sulfides + PGE) agrees well with physicochemical parameters in the C-O-H-S system. Stratified volatile concentration between partly (or completely) solidified layers of the Bushveld magma chamber is considered a key for the development of strati-

*Speaker.

form features in layered igneous complexes; it facilitates the understanding of both the large-scale adherence of the Merensky Reef to a stratigraphic horizon, and the small- to medium-scale disturbances such as potholes and other cross-cutting relationships.

The gradual evolution of such a melt-volatile system has been deduced on the basis of microscope and microprobe studies, and correlation with physicochemical data. This evolutionary trend receives strong support from fluid-inclusion studies, which are treated in a separate paper. The significance of the C-O-H-S system not only for Pt genesis, but for the evolution of layered igneous complexes in general, is underlined by Volborth & Housley (1984), who described complex graphite - sulfide - silicate - PGE associations from the Stillwater Complex.

REFERENCES

- STUMPF, E.F. & RUCKLIDGE, J.C. (1982): The platiniferous dunite pipes of the Eastern Bushveld. *Econ. Geol.* **77**, 1419-1431.
- VOLBORTH, A. & HOUSLEY, R.M. (1984): A preliminary description of complex graphite, sulphide, arsenide, and platinum group element mineralization in a pegmatoid pyroxenite of the Stillwater Complex, Montana, U.S.A. *Tschermaks Mineral. Petrog. Mitt.* **33**, 213-230.

FLUID INCLUSIONS IN MERENSKY AND BASTARD REEFS, WESTERN BUSHVELD COMPLEX

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Fluid inclusions in accessory quartz from the Merensky and Bastard Reefs have been examined. In the Merensky Reef the fluid inclusions represent the complete evolutionary trend during cooling. At least four generations of fluid inclusions occur:

1. Rare primary gas inclusions filled with CO₂ and CH₄. Sometimes traces of hypersaline brines with a minute halite daughter-crystal are present. The homogenization temperature is above 580°C.
2. Complex polyphase fluid-melt inclusions. These may contain up to eight different daughter-crystals, including several chlorides (?), silicates and, very rarely, oxides and sulfides. The volume ratios between solid, liquid and vapor phases are highly variable; extremes are large halite crystals completely enveloped by the host quartz and numerous melt-inclusions of different composition.
3. Abundant secondary three-phase H₂O-NaCl inclusions with more than 25 vol.% NaCl equivalent. Here the degree of filling is uniform. The temperature of homogenization was determined to be 230 ± 15°C.
4. Secondary two-phase H₂O-NaCl inclusions with NaCl equivalent from less than 25 vol.% to nil. These occur along healed cracks that can be traced back into sericitized plagioclase, and represent the latest generation. They are contemporaneous with the deuteric alteration of pyroxene and plagioclase. The homogenization temperature is 180 ± 30°C.

In contrast to the Merensky Reef, the fluid-inclusion association in quartz from the Bastard Reef and associated graphitic pegmatites is very simple. Here, primary (?) supercritical one-phase CH₄ inclusions, apparently parallel to growth zones of quartz, are by far the most abundant. CO₂ does not occur if intercumulus graphite is present; this agrees well with thermodynamic evidence. Fluid-melt inclusions are completely lacking; secondary H₂O-NaCl inclusions are rare.

The fluid-inclusion sequence sheds light on the late-magmatic history of the Merensky Reef. A genetic connection exists with several stages of fluid-melt immiscibility during cooling. Fluid-inclusion evidence also contributes to an explanation of the differences between the Merensky Reef with its PGE mineralization, and the barren Bastard Reef.

*Speaker.

THE FRACTIONATION OF THE PLATINUM-GROUP ELEMENTS AT THE ALEXO KOMATIITE, ABITIBI GREENSTONE BELT, NORTHERN ONTARIO

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The platinum-group-element (PGE) patterns from sulfides associated with the Alexo komatiite show variable degrees of fractionation. Massive sulfides at the contact between underlying intermediate volcanic rocks and overlying komatiites have the least-fractionated patterns (Pd/Ir 44). Net-textured sulfides that immediately overlie the massive sulfides have extremely fractionated PGE patterns (Pd/Ir 193). The disseminated sulfides in the overlying komatiite exhibit an intermediate degree of fractionation (Pd/Ir 108). The difference between the ore types can be explained by crystallization of monosulfide solid-solution from a sulfide liquid.

A further point of interest is that all the Alexo PGE patterns are extremely fractionated compared to that typical of komatiites (Pd/Ir 5–10). On the basis of field relationships and the lack of a source of Pd, this fractionation cannot be due to hydrothermal enrichment of the ore in Pd. Contamination of the komatiite magma prior to sulfide separation by a Fe-sulfide-rich sediment will not produce sufficient PGE fractionation. However, if the komatiite liquid with which the Alexo sulfides equilibrated had a lower Mg content (18–19% MgO) than komatiite liquid (28–30%) from a typical nickel sulfide deposit, then such fractionated patterns could be produced. The question arises: why does the degree of PGE fractionation increase with decreasing Mg content in komatiites? This is probably not related to partial melting, since it has also been shown to occur within a single komatiite flow. The only phase on the liquidus is olivine, and Ir will not enter olivine by solid substitution. It cannot simply be randomly included, since Pd would then also have an equal chance of being included, and no fractionation of the PGE would result. Therefore, we suggest that 1) Ir, because it is more strongly siderophile, formed small metal particles in the melt, and 2) olivine nucleated on these and settled Ir out of the melt.

THE PICKET PIN Pt–Pd DEPOSIT, STILLWATER COMPLEX, MONTANA

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The Picket Pin deposit is a zone of disseminated, PGE-bearing sulfide mineralization that occurs in the upper 10–30 m of An II, the largest anorthosite member (ca. 600 m thick) of the Stillwater Complex. Mineralization is present as centimetre- to metre-size podiform accumulations of sulfide found at and below a contact defined by a sharp textural and mineralogical change within the uppermost 5–15 m of An II. Below this contact, the footwall anorthosite consists of relatively coarse cumulus plagioclase and up to 20% intercumulus pyroxene (augite and inverted pigeonite). Within this unit, wedge-shaped interstitial grains of PGE-bearing sulfide are preferentially associated with pyroxene-poor rocks that contain interstitial quartz and apatite. The hanging wall consists of a medium-grained, largely monomineralic anorthosite (ca. 10 m thick) overlain by troctolite. Sulfide mineralization within these two hanging-wall members is barren of PGE (whole-rock assays < 5 ppb Pd). Directly below well-mineralized portions of the stratabound zone, podiform and pipelike bodies of sulfide occur to a depth of 150 m into the footwall anorthosite. These bodies are oriented with their long axis perpendicular to regional strike, and they may represent "feeder channels". Pyrrhotite, chalcopyrite and pentlandite are the predominant sulfides. Whole-rock values, normalized to 100% sulfide, show 44 ppm Pd, 35 ppm Pd, 1.4 ppm Ir, 14.6 wt. % Cu and 6.9 wt. % Ni. Relative to unmineralized anorthosite, the ore-bearing rocks are enriched in incompatible trace-elements. The transgressive sulfide "pipes" leading up to the stratabound portion of the deposit, the association of mineralization with residual, incompatible-element-enriched silicate assemblages and the Cu-rich nature of the sulfide assemblage are consistent with a model in which ore solutions were evolved and percolated upward during solidification of An II. Because of higher solidus temperatures, the hanging-wall rocks acted as an impermeable zone that trapped the upwelling ore-solutions beneath it.

*Speaker.

EVIDENCE FOR MINERAL REACTIONS AND METASOMATISM BY SILICA-UNDERSATURATED Cl-RICH FLUIDS IN THE MAIN Pt-Pd ZONE, STILLWATER COMPLEX, MONTANA

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Evidence for extensive volatile activity in the formation of the Main PGE zone of the Stillwater Complex is seen in the presence of pegmatitic textures and hydrous minerals. Biotite and apatite, which are most abundant in coarse-grained to pegmatitic rocks with >60% olivine, contain high Cl concentrations, the apatite containing 72% chlorapatite component. Anorthositic zones are developed asymmetrically about the olivine-rich layers, or as halos around podiform concentrations of olivine. A reaction involving chromite and biotite is evident in a biotite rim on chromite, and in the absence of chromite in olivine-rich rocks that contain abundant biotite. Because a fluid cannot be in equilibrium with all the assemblages present, observed rock-sequences may represent metasomatic reaction-zones. The anorthositic selvages around the olivine-rich rocks, in particular, are classic metasomatic zones in that they commonly are monomineralic, show sharp contacts with neighboring rocks and separate mineral-assemblages that are otherwise out of equilibrium. We interpret the olivine-rich rocks of OB I to have been regions of high concentration of fluid; we consider the anorthosites, previously interpreted as magmatic precipitates, to be zones of extensive leaching of mafic material. We propose a model in which progressive interaction of a (gabbro)norite protolith with a silica-undersaturated fluid leads to the following sequence of reactions: Olivine is produced by the incongruent dissolution of pyroxene. Chromium, liberated by the destruction of pyroxene and unable to be incorporated in olivine, is precipitated out as a chromium-bearing spinel. With increasing fluid/rock volume, chrome spinel itself becomes unstable and is replaced by biotite. As reaction advances, the olivine becomes more iron-rich. However, the total iron content in plagioclase decreases, and primary pyrite is no longer found as an exsolved phase in the sulfide assemblage, which suggests that the fugacities of both sulfur and oxygen decrease as the reaction proceeds.

A CONSIDERATION OF THE DEVELOPMENT OF PLATINUM-GROUP MINERALS IN LATERITE

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Suggestions have been made in the past indicating movement of platinum-group elements in solution at low temperatures. These suggestions have largely been disregarded or dismissed. Considerable evidence has now been gathered to show that the movement of gold in solution is aided by the conditions prevalent in the development of lateritic soil profiles, especially where humic or fulvic acids are present. In these conditions, gold may be dissolved, transported and redeposited to form large nuggets or small crystals with well-defined crystal faces. Similar solutions to those that can transport gold can equally act upon the platinum-group metals. The similarity in the chemistry of gold and the platinum-group metals indicates that this is not unreasonable.

Evidence that these criteria should be seriously examined is provided by photographs of two crystals of erlichmanite (Os,Ru) S_2 , obtained using a scanning-electron microscope. Both crystals are notable for their very smooth crystal-faces and sharp interfacial edges. One shows a plate-like development of faces meeting at a suture along the edges, which is particularly marked at the join of three faces. Another shows a feature in one face that again shows plate-like development over that face. In both cases it is clear that there has been some late-stage overgrowth of (Os,Ru) S_2 approximately 5 μ m in thickness on the outside of a grain that had earlier suffered some resorption, judging by the pitted underlying surface. The perfection of these crystals indicates that they have grown *in situ* in the laterite in which they were found. In the changing conditions to be found within a laterite, it is quite conceivable that partial resorption could be followed by crystal growth.

*Speaker.

PLATINUM-GROUP-ELEMENT GEOCHEMISTRY OF THE SERPENTINE HILL COMPLEX, DUNDAS TROUGH, WESTERN TASMANIA

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Field relations, petrology, and the PGE geochemistry of ultramafic and mafic rocks in the Middle Cambrian Serpentine Hill Complex indicate that it is an orthopyroxene-rich Alaskan-type complex and not an ophiolite, as previously described. The complex consists of multiple intrusions that formed an orthopyroxene-rich layered sequence, an olivine-rich sequence and a gabbroic unit. The layered sequence is composed of thin repetitive units of serpentinized olivine cumulate and orthopyroxene cumulate, and minor olivine-orthopyroxene cumulate. Locally these units are plagioclase-bearing. Primary structural features include unconformities, troughs, modal layering, slump structures, and syndepositional faults. The layered sequence is intruded by plagioclase-bearing dunite that locally contains chromite-rich zones. The chromite ranges from 0.64 to 0.69 in $\text{Cr}/(\text{Cr} + \text{Al})$ and 0.37 to 0.46 in $\text{Mg}/(\text{Mg} + \text{Fe})$. In places, it is layered and contains cognate xenoliths of the layered sequence. The two ultramafic sequences are cut by gabbroic rocks of variable grain-size. The Pt content in rocks of the complex ranges from 17 to 60 ppb and is highest in the gabbroic rocks, which also have the highest Pd content (max. 18 ppb). The ultramafic rocks of the layered and olivine-rich sequence contain no detectable Ir (<20 ppb) or Ru (<100 ppb) and less than 2 ppb Pd, in contrast to the chromitites, which contain up to 90 ppb Ir and 420 ppb Ru. Laurite and Os-Ir alloy occur in the chromitites. Comparison of chondrite-normalized PGE ratio of chromitites with those of ophiolite, stratiform, and komatiitic complexes shows distinctive differences. Although the overall chondrite-normalized pattern shows relative enrichment in Ru and Ir relative to Pt and Pd, similar to patterns for ophiolitic chromitite, Pt is more enriched with respect to chondrite than in ophiolites.

PRECIOUS-METAL ABUNDANCES IN KOMATIITES AND KOMATIITIC BASALTS: IMPLICATIONS FOR THE GENESIS OF PGE-BEARING MAGMATIC SULFIDE DEPOSITS

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The distribution of the precious metals Au, Pd, Ir, Os, Ru and the chalcophile elements Cu and Ni within an Archean komatiitic flow from Alexo, Ontario and the Phanerozoic komatiitic suite of Gorgona Island, Colombia, is compared with their abundances in magmatic sulfide ore-deposits associated with ultramafic volcanism.

The MgO contents of the komatiitic sequences range from about 11 to 31 wt.%. Variations of the lithophile elements, such as REE, Ti, Cr, Al and Zr, can be explained by olivine fractionation. The noble metals, Cu and Ni also plot along olivine fractionation trends: Au, Pd and Cu are incompatible and Ir, Os, Ru and Ni are compatible. The variations of Ir, Os and Ru can be modeled using olivine-liquid partition coefficients in the range 1.5–2.0.

Chondrite-normalized trace-element abundances in these komatiites are about two orders of magnitude lower than in sulfide deposits like Kambalda, Australia or Langmuir, Canada (Naldrett 1981) and are similar, in that both are depleted in Ir, Os and Ru relative to Au, Pd, Cu and Ni. However, the relative abundances of Ir, Os and Ru are chondritic within analytical uncertainty for both komatiites.

Within komatiitic rocks and associated sulfide ores, ratios of noble metals, such as Pd/Ir, Au/Ir,

*Speaker.

Pd/Os and Pd/Ru, show a negative correlation with MgO content. This is due to the compatibility of Ir, Os and Ru relative to Au and Pd with respect to olivine; therefore, these ratios strongly depend on the degree of melting required to generate the silicate host-liquid and the amount of fractionated olivine at the time of sulfide segregation.

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A FLUID-DYNAMIC MODEL FOR THE MERENSKY REEF POTHOLES

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An important feature of the Merensky Reef is the presence of 'potholes' in its base. These are areas where some of the cumulates underlying the Reef are missing and the base of the Reef occurs up to 30 m below its normal stratigraphic position. Potholes vary in diameter from a few metres to several thousand metres. The smaller potholes are generally circular in plan and have rounded cross-sections. The larger potholes are less regular. They have flat bottoms, with their bases at specific stratigraphic levels, such as the olivine-rich Pseudo Reef Marker.

The cyclic unit that hosts the Merensky Reef is generally attributed to the entry of a new pulse of olivine-bronzite-saturated magma. This new magma has the capacity to melt the plagioclase cumulates that form the floor of the chamber. Since the products of erosion are light, they are swept away by turbulent convection and replaced by hot uncontaminated magma, allowing erosion to continue. Thus the potholes may be the products of efficient thermal erosion.

Thermal erosion, leading to the release of a light fluid, has been modeled in a series of experiments in which a block of ice was melted into an overlying salt solution. Two features of the experiments are noteworthy: firstly, melting produced a pitted texture on the surface of the ice, similar to the dimpled contact between the Merensky Reef and the underlying plagioclase cumulates, and secondly, small holes in the ice rapidly expanded into larger holes that are circular in plan and rounded in section. The similarity between these structures and potholes suggests that they formed by similar processes. Erosion in the larger potholes was arrested at olivine-rich layers because the products of thermal erosion were dense and could not convect away from the melting surface.

THE ROLE OF CONTAMINATION IN THE EVOLUTION OF THE PLATREEF OF THE BUSHVELD COMPLEX

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The Platreef is a thick (> 100 m) marginal feldspathic pyroxenite that transgresses a dolomitic and granitic floor. It is overlain by two-pyroxene gabbro of the Main zone. A break in orthopyroxene compositions at this contact suggests that magma was added at this level. Trace-element geochemical data through vertical profiles of the reef show differences depending upon type of footwall. Against a granitic floor the basal portion is heterogeneously contaminated by a melt or fluid from the granite (initial $^{87}\text{Sr}/^{86}\text{Sr}$

*Speaker.

ratios vary from 0.7127 to 0.7226 in the reef). Overlying the dolomitic footwall, the Platreef shows less evidence of siliceous contamination. The extent of dolomite assimilation is difficult to quantify. The dolomite appears to have been metasomatically altered by a granitic phase (high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio 0.72 and high Rb content) derived from below the dolomite.

Cumulus plagioclase and pyroxene in the upper part of the reef formed prior to contamination, interstitial material crystallizing from a contaminated liquid. The lowermost rocks of the Main zone also contain a minor proportion of this contaminated liquid. The tenor of Pt in the upper reef precludes sulfide formation from interstitial liquid; hence separation of the sulfide liquid predates the process of contamination by siliceous material. In contrast, sulfides in the lower reef may be produced by the contamination.

Some siliceous contamination has influenced the trace-element geochemistry of the Platreef, but the extent is dependent on the nature of the immediate footwall. Sulfide mineralization does not appear to be controlled only by the extent of siliceous contamination.

GEOCHEMICAL RELATIONSHIPS IN THE SOUTH RANGE OF THE SUDBURY IGNEOUS COMPLEX

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Whole-rock geochemical samples were taken approximately every twenty metres across the Sudbury Igneous Complex along the Blezard traverse and at three-metre intervals along boreholes drilled through the basal four hundred metres of the Complex at the Murray mine. Differentiation trends, as shown by Pearce diagrams, were compared with the petrography. The Blezard traverse samples exhibit differentiation trends that correlate with the mineralogical variations between the quartz-rich norite, the South-Range norite, the quartz gabbro and the granophyre.

The samples from the Murray section illustrate three distinct petrological trends. The upper two hundred metres correlate with the quartz-rich South-Range norite. The second trend, denoted as the South-Range mafic norite, corresponds to a twenty-metre-thick orthopyroxene cumulate at the base of the quartz-rich norite, and the third trend corresponds to a sixty-metre-thick zone of weakly mineralized inclusion-bearing sublayer norite located below the South-Range mafic norite and above the sulfide-rich sublayer. The sublayer zone is also an orthopyroxene cumulate, and the orthopyroxene and plagioclase crystals become progressively more altered toward the footwall. The sublayer norite is enriched in silica relative to the South-Range mafic norite; the increase is interpreted to be the result of contamination from the inclusions. The South-Range mafic norite is correlated with the mafic norite on the North Range. Magma convection is cited as a possible mechanism for depositing these units in footwall troughs, such as that found at Murray.

The Pearce diagrams confirm that the composition of the outer margin of the quartz-rich norite is representative of the original composition of the Igneous Complex. The fractionation trends are similar to those found in tholeiitic intrusions such as the Palisades Sill and the Tasmanian dolerites.

PLATINUM-GROUP ELEMENTS AND VARIATIONS IN CHROMIAN SPINEL IN THE CRYSTAL LAKE GABBRO, THUNDER BAY, ONTARIO

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Recent studies have revealed the presence of four chromian spinel horizons, each belonging to a magmatic cycle. The four cycles are superposed. The first three horizons lie in the lower portion of the cycles and contain irregular chromian-spinel-rich bodies disseminated over 1-3 metres. The fourth horizon lies in the lower portion of the last magmatic cycle and contains four chromian-spinel-rich stratiform layers whose thickness varies from 2 to 10 cm.

*Speaker.

Chromian spinel occurs as octahedral, spherical and irregular inclusions in poikilitic plagioclase, olivine and pyroxene; inclusions of different shape can be observed in the same host silicate.

Electron-microprobe analyses have revealed the following compositional variations from cycle I to cycle IV, as well as variations from core to rim of single crystals: 1. a) Chromian spinel in the disseminated bodies has a chaotic distribution and a wide range of chemical variation. b) Those of the upper stratiform layers have a regular trend and restricted range of variation. c) Composition variation in single crystals, from core to rim, is greater in rounded than in euhedral crystals. 2. The following chemical variations have been observed from cycle I to cycle IV: increase of Al and Mg, and decrease of Cr and Ti. 3) The concentration of platinum-group elements has been determined by neutron activation. Their variations are examined in the different cycles. In each case, the concentration of palladium exceeds that of platinum.

PLATINUM-GROUP ELEMENTS IN THE KOMATIITE-HOSTED Fe-Ni-Cu SULFIDE DEPOSITS AT KAMBALDA, WESTERN AUSTRALIA

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The concentrations of all platinum-group elements (PGE) and gold in monthly composite samples of mined ores have been determined by neutron-activation analysis. Average values from a typical ore-shoot of medium-Ni tenor (10% Ni in 100% sulfides) are: Os 480, Ir 230, Ru 980, Rh 320, Pt 1650, Pd 2050, Au 500 (all values are in ppb and are recalculated to 100% sulfides). These values, and chondrite-normalized values, are similar to those reported from other komatiite-hosted Ni ores. Ir, Ru, Rh and Pd correlate strongly with Ni (r 0.73 to 0.92), whereas Pt (r 0.50) and Os (r 0.63) correlation is only moderate. Au does not correlate with Ni (r -0.28).

Geochemical profiles of PGE values normalized to 100% sulfides through typical ore-zones show depletion of Pt, Pd and Au in massive sulfides relative to overlying matrix and disseminated sulfides, whereas the other PGE have a more uniform distribution through these ore types. Pt, Pd and Au are strongly concentrated at the contact between footwall metabasalt and the massive sulfides and in small stringers of sulfide within the footwall metabasalt. Other PGE are concentrated to a lesser extent at this position. Some magnetite-rich selvages immediately above massive ores are depleted in Os, Ir and Ru.

Pt, Pd and Au largely occur in discrete phases within sulfide ores, but no discrete Os, Ir, Ru or Rh phases have been recognized. These elements may largely occur in solid solution in pentlandite, and their more regular distribution through the ore zone may be due to the fact that pentlandite rarely is affected by metamorphic alteration-reactions. The Pt, Pd and Au concentration at the base of massive ores may be attributed to stress-induced diffusion during metamorphism. The diversity of PGE contents of bulk-ore samples is similar to the variation in major-element composition and is due to variable $f(\text{O}_2)$ in the sulfide-silicate system prior to eruption.

PGE DISTRIBUTION IN KOMATIITIC AND THOLEIITIC VOLCANIC ROCKS FROM MUNRO TOWNSHIP, ONTARIO

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The concentrations of Pt, Pd, Ir and Au were determined in two peridotitic komatiite flows from Spinafex Hill, Fred's flow (a layered komatiitic flow) and Theo's flow (a layered tholeiitic flow), all from Munro Township, Ontario. Analyses were done by radiochemical neutron-activation. The Munro data

*Speaker.

are compared with PGE in mantle rocks and komatiite-hosted nickel sulfide ores to evaluate trends of PGE fractionation during low-pressure fractional crystallization, partial melting in the mantle, and separation of an immiscible sulfide liquid from silicate magmas.

Fractionation trends in the komatiitic flows, as indicated by comparison of PGE in spinafex-textured and cumulus facies, suggest that Pt, Pd and Au behave as incompatible elements that fractionate preferentially into the melt. Ir, on the other hand, fractionates toward some solid phase, probably olivine. These trends are much weaker in the tholeiitic flows.

By comparison with PGE proportions in meteorites and some mantle nodules, all three flows are strongly depleted in Ir. In the Spinafex Hill flows and in Fred's flow, Pt, Pd and Au are in approximately chondritic proportions. Assuming chondritic PGE ratios in the mantle source-region, the PGE ratios in the flows imply that Ir was preferentially retained in the mantle residuum left after partial melting. The nearly chondritic Pt/(Pt + Pd) values in the Spinafex Hill komatiitic peridotite flows are approximately twice those observed in nickel sulfide ores hosted in komatiitic rocks, suggesting a preferential partition of Pd into immiscible sulfide relative to Pt. The Pt/Pd ratio may be a useful indicator in some magmas of whether sulfur saturation has been experienced.

VARIATION IN PLATINUM-GROUP-MINERAL DISTRIBUTION AND COMPOSITION FROM THE PROTEROZOIC DONALDSON WEST NI-Cu DEPOSIT, NORTHERN QUEBEC

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The Donaldson West Ni-Cu deposit is hosted in an Aphebian ultramafic sill in the eastern Cape Smith - Wakeham Bay fold belt of northern Quebec. Metallurgical drill-hole 160-224 was examined at 1- to 3-m intervals over the basal 80 m of the 150-m-thick sill. Primary magmatic Fe-Ni-Cu sulfides at the basal contact grade from massive through net-textured to disseminated sulfides. Sulfide mobilization during pervasive serpentinization and regional metamorphism in the lower net-textured sulfides resulted in a gradation to reverse net-texture. Thin, Cu-rich massive seams, occurring within the net-textured to reverse net-textured zone and at the disseminated/net-textured contact, are shear- or foliation-related and contain calcite and dolomite. Supergene alteration is very rare and restricted to late fractures.

PGM (PdSb, and PdSbTe) and Pd-bearing ullmannite from disseminated sulfides are rare and fine grained (< 50 μm). The abundance, diversity and size of the PGM increase in the net-textured sulfides. PdSb, PdSbTe and PtAs₂ are common and attain 150 μm in length. Trace amounts of PdTe₂ and an unknown Pd₃Sb₂Te₂ occur. However, many PGM are related to seams or veinlets of mobilized sulfides, and occur with electrum, Ag₂Te, NiTe₂, Ni-Co arsenides and Ni-Co pyrite. PGM within the reverse net-textured sulfides are smaller (< 50 μm) and less abundant. Whereas the diversity of PGM remains similar, NiTe₂ is more common; electrum, Ag₂Te and Co-arsenides were not observed. Massive sulfides have metamorphic textures, low Pt, Pd and Au contents, high Os, Ir, Ru, Rh, Co, As, Sb, Bi and Te contents, and fine PtAs₂ and abundant large grains of Pd-bearing NiTe₂. Values of the Pt/(Pt + Pd) ratio for disseminated, most net-textured, and massive sulfides range between 0.45 and 0.70. Reverse net-textured sulfides are depleted in Ni and Pt contents. Cu-rich specimens, modified net-textured, and reverse net-textured specimens have a lower ratio (0.20 to 0.45), reflecting Pt depletion.

THE SOLUTION OF NICKEL OXIDE IN MAFIC MAGMAS: A SIMPLE MODEL

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In our recent study (Doyle & Naldrett 1984), we used the compositional dependence of the activity of ferrous oxide to argue that divalent cations mix ideally on the sites they occupy in mafic liquids. This hypothesis is directly analogous to that typically used to account for the well-known approximately ideal solution behavior observed in olivine and orthopyroxene.

*Speaker.

The simple model accounts for the data in $\text{SiO}_2\text{-FeO-(Mn, Mg)O}$ melts and in three Matrix-FeO-MgO ternary systems contoured by us for a_{FeO} using results of 200 experiments on synthetic analogs of MORB, standard diabase W-1 and high-TiO₂ mare basalt, respectively. Importantly, this finding greatly facilitates determination of the change in solid/liquid partition coefficients and properties such as magma density with compositional variation of the mafic melt.

Because the available activity – concentration relations for Ni-Mg oxide (Evans & Muan 1971) and silicate (Campbell & Roeder 1968) solid solutions indicate that nickel also is approximately randomly distributed with magnesium, we have equilibrated a series of aluminosilicate melts with metallic nickel at controlled oxygen fugacity to test the ideal-mixing hypothesis in nickel-bearing mafic liquids. All compositions lie in a ternary system, of the type Matrix-NiO-MgO, containing a synthetic analog of W-1. Runs are performed on both high- and low-nickel starting materials, so that the locus of each isoactivity curve is well constrained.

The simple-solution model predicts that the activity of NiO in a ternary melt, at a given mole fraction of Matrix ($X_{\text{Matrix}} = 1 - X_{\text{NiO}} - X_{\text{MgO}}$), is related to the value in the corresponding NiO-Matrix (Mg-free) binary liquid by the equation,

$$a_{\text{NiO}}^{\text{ternary}} = a_{\text{NiO}}^{\text{binary}} \times [\text{Ni}/(\text{Ni} + \text{Mg})].$$

Our preliminary data are consistent with this equation, suggesting that Ni and Mg do, indeed, mix ideally in mafic magmas.

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CRYPTIC VARIATIONS WITHIN CHROMITITES OF THE UPPER CRITICAL ZONE, NORTHWESTERN BUSHVELD COMPLEX

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The close association of PGE with chromite calls for the appraisal of structures, textures and composition of chromitites in the development of genetic models. Microprobe studies show that cryptic variations in successive chromitite layers within cyclic units (e.g., UG1 unit) are consistent with fractionation of limited volumes of melt. Individual chromitite bands within composite layers (e.g., UG-2) may have distinctive compositions, but all exhibit long-range compositional trends superimposed on short-range homogeneity. The accessory chromite lies within a compositional range substantially different from that of massive chromitites; reaction with residual liquids and subsolidus reactions were significant. Recrystallization of chromitites was ubiquitous, but the importance of *in situ* growth is shown by relict textures. Textural studies and mineral chemistry indicate that chromitite layers form largely by *in situ* bottom crystallization and that processes involving long-range crystal settling or deposition from density currents were not important. Post-depositional densification of chromitite layers occurred in response to prolonged annealing at high subsolidus temperatures rather than by adcumulus growth. These findings are significant with respect to PGE mineralization in the UG-2 chromitite layer.

*Speaker.

MINERALOGY OF MELONITE-GROUP PGM AND OTHER TELLURIDES FROM THE IVREA-VERBANO BASIC COMPLEX, WESTERN ITALIAN ALPS

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Ferrario *et al.* (1982) pointed out the existence of subeconomic anomalies of Pd and Pt in the Ivrea-Verbano layered igneous complex. These metals are mainly associated with Fe-Ni-Cu sulfide ores of the Sudbury type, related to ultramafic rocks with two different modes of occurrence: 1) as fractionation layers at various stratigraphic levels, in the basic complex (type A), and 2) as cross-cutting pipe-like bodies emplaced in the upper part of the complex, or injected into the roof country-rocks as offsets (type B). In the investigation of Ferrario *et al.* (1982), only the Pd anomalies in type-A sulfide ores were documented. Specific phases were found to occur as minute grains dispersed within the main sulfides (pyrrhotite, pentlandite and chalcopyrite). These grains were only qualitatively identified as Pd-tellurides.

The present work reports the results of a more detailed investigation, which revealed the presence of PGM also in type-B sulfide ores. Accurate quantitative microprobe analyses were carried out on both types of occurrence; this yielded a more complete mineralogical characterization of all PGM and other associated minerals. The larger grains (15 – 30 μm) were located by careful examination of 3-cm-diameter polished sections by reflected-light microscope; the smaller ones (15 – 5 μm and less) were detected by systematically scanning the same sections in the SE-image mode in the microprobe.

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THE NATURE AND SIGNIFICANCE OF IGNEOUS "POTHOLE" STRUCTURES IN SOME LAYERED INTRUSIVE COMPLEXES

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Samples from three circular depressions (potholes) that occur in the footwall of the Merensky Reef of the Bushveld Igneous Complex show an increase in total carbon and a decrease in intrinsic $f(\text{O}_2)$ values from the margin to the centre. Morphological types of potholes include: (a) regular shallow depressions, (b) irregular shallow depressions, (c) steep-sided "disrupted" potholes, (d) flat-bottomed "rolling reef" or "rollover" potholes, (e) double potholes. These range from tens to hundreds of metres across and as much as 97 m deep. In most the footwall strata are sharply truncated at the pothole sides, but quasiconformable (over downwarped and thinned? footwall units) and partially truncated variants (with downwarped footwall units) are apparent. That these potholes and their much rarer positive counterparts (koppies) represent some unusual magmatic erosion by a fresh batch of magma may account for the former, but not the two latter footwall conditions, nor for the geochemical gradients indicated by our limited sampling. Methane-rich magmatic fumaroles in the footwall rocks could produce these unusual erosion features if they discharged into an overlying convecting(?) melt. The similarity in isotopic composition of graphite from both the Stillwater and Bushveld Complexes is noteworthy.

Similar features are suspected for the J-M Reef in the Stillwater Complex and are known in the footwall rocks of the UG-2 chromitite seam on Western Platinum in the Bushveld Complex, but not in any of the other workings on chromitite or magnetite seams. The association with the PGM-bearing horizons may be more than fortuitous: the sulfide phases may be precipitated by a critical $f(\text{O}_2)$ - $f(\text{S}_2)$ difference, triggered by dissemination of methane into the residual magma. This hypothesis could be verified by sampling different morphological types laterally and vertically away from a pothole centre.

*Speaker.

CONTRASTING PETROLOGY AND PGE GEOCHEMISTRY OF ZONED ULTRAMAFIC COMPLEXES, KLAMATH MOUNTAINS, CALIFORNIA AND OREGON

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Postorogenic zoned ultramafic-mafic complexes have been identified in the Klamath Mountains, western U.S.A. The complexes range in age from 142 to 163 Ma and variously intrude metavolcanic, metasedimentary, and ophiolitic cumulate ultramafic to gabbroic rocks. The Tincup Peak unit consists of a sequence of olivine clinopyroxenite, wehrlite, clinopyroxenite, magnetite clinopyroxenite, feldspathic hornblende-magnetite clinopyroxenite, and hornblende gabbro; the Lower Coon Mountain pluton consists of layered augite-rich lithologies that intrude each other in the sequence plagioclase + augite cumulate ($\pm$ magnetite), augite-olivine cumulate, olivine-augite cumulate, and olivine cumulate; the Chancelulla Peak unit consists of biotite-bearing clinopyroxenite and minor interlayered dunite and wehrlite, later intruded by hypabyssal gabbroic rocks. Augite compositions differ slightly in the three complexes, ranging from $\text{En}_{41.2}$ to $\text{En}_{47.3}$, $\text{Wo}_{46.9}$ to $\text{Wo}_{50.6}$, and $\text{Fs}_{4.9}$ to $\text{Fs}_{9.9}$. Intervals of layered cumulus magnetite ($\pm$ ilm) and interstitial magnetite occur at Tincup Peak and Coon Mountain. All three contain disseminated pyrrhotite + pentlandite + chalcopyrite, but the Chancelulla Peak unit has lenticular zones of disseminated to interstitial sulfides along its contacts with hornfelsic rocks. Chondrite-normalized PGE ratios suggest slight differences between the complexes and important differences between these complexes and ophiolitic rocks. Rock, soil, and stream-sediment samples from the complexes contain no detectable Ir (<20 ppb) or Ru (<200 ppb) and rarely detectable Rh (<1 ppb); however, they contain as much as 230 ppb Pt and 191 ppb Pd. Both stream sediments and soils appear to be enriched in Pt + Pd, compared with underlying rocks. Some of the data suggest that the ratio $\text{Pd}/(\text{Pd} + \text{Pt})$ is higher in the later gabbroic rocks than in the ultramafic sequences.

NEW MICROPROBE DATA ON PLATINUM-GROUP MINERALS AND THEIR RELATIONSHIPS TO METAMORPHISM AND DEFORMATION OF HOST Ni-Cu SULFIDE DEPOSITS

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Platinum-group and Au, Ag minerals have been identified and analyzed by electron microprobe from 12 nickel-copper deposits in Canada, selected to provide a range of age, host rock, metamorphic overprint and degree of mobilization. PGM occur within and at grain boundaries of all major sulfide minerals. In strongly metamorphosed and oxide-rich deposits, the PGM, often with Ag minerals, occupy pressure shadows of magnetite. Merenskyite ($n = 79$), moncheite (11) from a variety of Archean deposits and borovskite (4) from Wellgreen have significant Ni contents compared to other tellurides. Palladian antimonides are common in deposits from the Proterozoic Smith Belt.

Platinum minerals are not nearly as common as palladium minerals in spite of high assays for Pt, although where As contents are high, sperrylite occurs, commonly with Ni-Co arsenides, as small, generally skeletal grains (Cape Smith Belt, Thompson Belt). In As-poor sulfides, sperrylite is rare, and the location of Pt was not established. However, in sulfides that have undergone medium-grade metamorphism or, especially, strong deformation (Thierry, Kanichee, Gordon Lake), platinum content of merenskyite (or moncheite abundance) is considerably higher than that of sulfides at lower grade.

*Speaker.

Rapid cooling of magmatic sulfides or reheating to greenschist-facies conditions causes exsolution and collection of PGE, mainly as Pt-poor tellurides with varying Ni contents. These are generally retained in disseminated or massive sulfides. The palladium was probably derived from pentlandite; the location of Pt is unclear. However, on strong reheating, or deformation, platinum-group elements (especially with copper and silver) may migrate and deposit (commonly with carbonates and quartz) in fractures within or adjacent to the mafic or ultramafic rocks.

PLATINUM-GROUP MINERALS FROM THE KAMBALDA NICKEL DEPOSITS, WESTERN AUSTRALIA

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The Archean Kambalda magmatic nickel sulfide ores have been estimated to have a bulk composition of Ni 2.96%, Cu 0.22%, Co 0.07%, S 8.09%, Pt 326 ppb, Pd 425 ppb, Os 110 ppb, Ir 60 ppb, Ru 220 ppb, Au 339 ppb, Ag 1170 ppb. However, descriptions of discrete PGE phases are restricted to a few *in situ* occurrences that have been observed during routine documentation of mine development.

A recent study of gravity concentrates from the gold-recovery circuit of the Kambalda nickel mill enabled an assessment to be made of the nature, relative abundance and compositional variability of PGE minerals present in the nickel deposits. The major platinum minerals are sperrylite and moncheite, and the major palladium minerals are sudburyite, merenskyite, stibiopalladinite and palladoarsenide. Palladian melonite, which contains up to 10 wt.% Pd, is also an important host for the PGE. Sperrylite and sudburyite are by far the most abundant discrete minerals in the gravity concentrates.

Bulk samples (20–100 kg) of ore were collected to assess both the distribution and size range of sperrylite and sudburyite. Samples included massive ores, matrix ores, disseminated ores, stringer zones, gold-bearing quartz-carbonate veins, and younger intrusive porphyries. Sperrylite was recovered in gravity concentrates from massive-sulfide ores from stopes in Juan Shoot and Ken Shoot, and from chalcopyrite-rich massive-sulfide ores from ore stockpiles at Ken Shoot and the Kambalda nickel mill. Sudburyite, moncheite, merenskyite and palladian melonite occur in chalcopyrite-rich stringers, hydrothermal veins and reaction zones, indicating that their formation may be related to postmagmatic processes, in particular to metamorphic segregation of sulfides and to the interaction of the ore sulfides with younger hydrothermal fluids.

SIGNIFICANCE OF A FLUID PHASE IN PLATINUM-GROUP-ELEMENT CONCENTRATION: EVIDENCE FROM THE CRITICAL ZONE, BUSHVELD COMPLEX

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The relationships of chromitites and platinum-group minerals to pegmatitic rocks, hydrous minerals, and abundant fluid inclusions in postcumulus quartz and feldspar were examined in a normal "reef" section (Union Section) from UG-1 to the Bastard Reef. Microprobe and SEM analyses of chromite (and coexisting cumulus and postcumulus minerals) revealed narrow compositional ranges in UG-1 and UG-2 of X_{Fe} (0.537–0.593), Y_{Cr} (0.561–0.576), Y_{Al} (0.331–0.377), $Y_{Fe^{3+}}$ (0.055–0.098). UG-2 chromite is slightly enriched in TiO_2 (0.77–1.0 wt.%) compared to that from UG-1. Merensky Reef chromite has higher $Y_{Fe^{3+}}$ (0.14) and Y_{Cr} (0.522), Y_{Al} (0.338), TiO_2 (0.87 wt.%). Chromite from pyroxenite has even higher $Y_{Fe^{3+}}$ (0.120–0.230); Y_{Cr} is 0.590–0.673 and X_{Fe} is 0.739–0.897. Pseudoreef chromite has very high TiO_2 (5.30%) and $Y_{Fe^{3+}}$ (0.324), X_{Fe} (0.858), and low Y_{Cr} (0.423). Chromite from pegmatitic pyroxenite of the Merensky Reef has the lowest Y_{Cr} (0.384) and the highest $Y_{Fe^{3+}}$ (0.344) of all chromite samples examined.

Two-pyroxene temperatures range from 1025 to 923°C below and from 990 to 920°C above the

*Speaker.

pseudoreef. Postcumulus mica (phlogopite with as much as 6.75% TiO_2) occurs throughout the Upper Critical Zone. Values as high as 1.0% Cl and 1.7% F were recorded in 170 analyses of mica. X_{Fe} and Cl contents of mica are positively correlated with X_{Fe} of coexisting chromite; no correlation is apparent with X_{Fe} of orthopyroxene.

Inclusions of mica in chromite are very sodic (as much as 6.4% Na_2O), frequently in contact with En_{90} , Wo_{46} , En_{47} , Fs_7 , rutile and sulfide inclusions. They are Cl-rich just above of PGE-bearing reefs. Fe variations in chromite imply rapid increases and decreases in $f(\text{O}_2)$ that may relate to varying partial pressure of fluids; corresponding variations in Cl contents of mica and occurrences of fluid inclusions indicate an important role for fluids in modifying the nature of liquidus phases.

THE SYSTEM Pd-Co-S AT 1000, 800, 600 and 400°C

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The condensed-phase system Co-Pd-S has been studied at 1000, 800, 600 and 400°C using dry charges annealed in evacuated silica-glass tubes. The products were evaluated by means of microscopy, microprobe analyses and X-ray diffraction. The system was chosen as a simple isoelectronic model for the system with Fe:Ni ~ 1:1.

At 1000°C, the only solid phase found was Co_{1-x}S ; it dissolves up to 4.2 wt.% Pd.

At 800°C, the sulfide is limited to the broad region at 30-45 at.% S in equilibrium with either Pd-Co alloys or sulfides. Co_{1-x}S dissolves up to 2.8 wt.% Pd in equilibrium with Pd and melt.

At 600°C, the sulfide melt is reduced to a small area adjacent to high-Pd sulfides. Co_{1-x}S dissolves 0.5 wt.% Pd, whereas Co_9S_8 has up to 7.5 wt.% Pd. Solubility of Co in Pd_4S , which was high at 800°C, drops to 0.9 wt.%. A large solubility gap opens between Co and the Pd-Co alloy coexisting with Co_9S_8 .

At 400°C, the Co_9S_8 -Co- Pd_4S association replaces the Co_9S_8 -Co-(Pd,Co) association from 600°C. The Co-rich sulfides do not coexist with Pd alloys. Co_9S_8 dissolves 3.0 wt.% Pd. The solubility of Co in PdS drops from ~0.7 wt.% at 800°C to ~0.4 wt.% at 400°C. Co_{1-x}S is unstable at 400°C.

DISCONTINUITIES AND VARIATIONS OF Sr-ISOTOPE SYSTEMATICS IN THE MAIN ZONE OF THE BUSHVELD COMPLEX, AND THEIR RELEVANCE TO PGE MINERALIZATION

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New Sr-isotope data from the Main Zone of the Western Bushveld Complex in the vicinity of the Union platinum mine indicate that a number of influxes of magma followed a major input at the Merensky level documented previously. Values of the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (R_0) of the Main Zone are elevated (0.7075 to 0.7090) compared with those below the Merensky unit (0.70635). At the putative position of the "Pyroxenite Marker", there is another major reversal to a lower R_0 (~ 0.7073). The magmatic evolution of the Main Zone was initiated by a large influx of magma with a high R_0 that dominated its subsequent evolution, until a large influx of magma at the Pyroxenite Marker initiated that of the upper zone. There is considerable variation in the Main Zone, indicating input and mixing of magmas with higher and lower values of R_0 . The variation of R_0 with respect to stratigraphic height can be explained by a double-diffusion convection mechanism coupled with the introduction of magmas as "plumes" or as "jets". The first major influx was a plume with a high R_0 (> 0.7090) into a chamber containing magma with a lower R_0 (0.70635). This resulted in a major upward shift in the value of R_0 and a stratified liquid with a continuous vertical variation in R_0 . The stratified liquid formed a double-diffusion convection system and started crystallizing from the base upward. Other influxes of magma, with both lower and higher R_0 , behaved as jets.

The PGE mineralization of the Merensky unit is associated with large *plume*-type additions of magma, where efficient scavenging of PGE by exsolved sulfide droplets was possible. Jet inputs do not provide conditions for efficient mixing and thus are poor targets for exploration.

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PGE ABUNDANCES IN THE LOWER AND LOWER CRITICAL ZONES OF THE EASTERN BUSHVELD COMPLEX

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Forty whole-rock samples representing the principal silicate lithologies of the Lower and the lower Critical Zone of the eastern Bushveld Complex were analyzed in duplicate for Ir, Rh, Pd and Au. Ir ranges from 0.1 to 2.2 ppb, with scattered values greater than 4 ppb. No trends are discernable up the layered sequence. Dunites (85–98% olivine) have a lower Ir content (1 ppb) than the pyroxenites (60–96% orthopyroxene). Higher Ir values correlate with higher Ru and, on occasion, with higher Rh abundances.

Ru has a wide range, from 2 to 15 ppb. Rocks of the lower part of the sequence generally have less than 5 ppb and those of the upper part of the sequence have more than 5 ppb Ru. Rh ranges from 1.5 to 5 ppb, with sporadic values greater than 5 ppb. There is a tendency for Rh to be slightly greater in concentration in the olivine-rich part of the section.

Pt ranges from 10 to 135 ppb; the majority of the values are less than 30 ppb. There is no correlation of rock type with the Pt content. Pd was determined in all the samples but was detected (4 ppb) in only five. These occur in the Critical Zone and usually correlate with the higher Pt abundances. Au concentrations are generally less than 2 ppb but range up to 8 ppb. The higher Au values correlate with higher Ir abundances, but the opposite is not always the case.

In all instances, the sporadically higher PGE contents occur in the upper part of the sequence, *i.e.*, the lower Critical Zone. The single Marginal Norite sample analyzed contains higher PGE than the overlying Lower Zone pyroxenites. Standard XRF analyses for major elements, selected trace elements, and mineralogical data are incorporated in the interpretation.

EXPERIMENTAL STUDIES ON THE SOLUBILITY AND DISTRIBUTION OF PLATINUM-GROUP ELEMENTS IN BASE-METAL SULFIDES IN PLATINUM-GROUP-MINERAL DEPOSITS

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The present laboratory research examines the solubility of Pt, Pd, Rh and Ru in the main base-metal sulfides that occur in PGE deposits: pyrrhotite/troilite, pyrite, chalcopyrite/isotropic Cu–Fe–S solid solution, and pentlandite. Compositions of PGE sulfides that are in equilibrium with the above base-metal sulfides saturated with PGE are determined as well. Two distinct temperatures are studied: 900°C (related to the magmatic–submagmatic range) and 500°C (related to postmagmatic–pneumatolytic processes). PGE-rich solid solutions are being annealed at 300°C for an extended period in order to study low-temperature exsolution phenomena. At the present stage, the basic patterns of PGE solubility in the studied sulfides have been established.

At 900°C up to 2.2. wt.% Pt, 1.4 wt.% Pd or 3.6 wt.% Ru can dissolve in pyrrhotite at high S fugacities. The solubilities are minimal at the troilite composition. At 500°C up to 0.5 wt.% Pd can dissolve in S-rich pyrrhotite, but the solubilities of Pt and Ru are already below the microprobe detection-limits. The solubility of Rh in pyrrhotite presumably reaches 44 wt.% Rh at 900°C but only 5.8 wt.% at 500°C. Exsolution phenomena were observed in PGE-rich pyrrhotite on quenching. Pyrite does not dissolve appreciable amounts of PGE at 500°C.

Ru and Rh can completely occupy the octahedral positions in pentlandite at 500°C. Pd occupies this position only incompletely, whereas no Pt enters pentlandite beyond the microprobe detection-limit at this temperature. No Ru and Rh dissolve in *iss* or chalcopyrite at the temperatures studied. Cu–Fe–S melts with high Pt contents were found at 900°C. They are related to the bornite and *iss* regions and show that Cu-rich sulfide melts can concentrate platinum. A range of PGE sulfides and PGE alloys with dissolved Fe, Ni and Cu occur in equilibrium with the PGE-containing base-metal sulfides.

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APATITE AND BIOTITE FROM THE STILLWATER AND BUSHVELD COMPLEXES AND THE NATURE OF HYDROTHERMAL ACTIVITY

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That the PGE-rich zones of both the Stillwater and Bushveld Complexes have been affected by volatile-rich melts, magmatic or high-temperature hydrothermal fluids, or both, is indicated by the presence of pegmatitic rocks and relatively high modal abundances of volatile-bearing minerals. Such minerals, particularly apatite and biotite, can be used to characterize this volatile-rich environment.

Apatite occurs as an accessory mineral in OBI (the main Pt zone), in the PGE-bearing Pickett Pin zone, and in the quartz-bearing anorthosites of the Stillwater and in the Merensky and UG-2 members at the Rustenburg and Western Platinum mines of the western Bushveld. Its molar $\text{Cl}/(\text{Cl} + \text{F} + \text{OH})$ ratio ranges from 1 to 0.1. These values are greater than those of cumulus apatite from the Upper Zone of the Bushveld or from the Skaergaard (Nash 1976) and Kiglapait (Huntington 1979) intrusive complexes. The intercumulus Stillwater and Bushveld apatite also contains a high concentration of Ce_2O_3 (up to 0.6 Wt.%) and La_2O_3 (up to 0.3%).

Biotite is common in OBI and in the olivine-rich rocks of the Ultramafic Series of the Stillwater and throughout most of the Bushveld. Again, it is relatively Cl-rich. For example, Merensky biotite typically contains 0.3–0.7 wt. % Cl and that from OBI, 0.2–0.3% Cl, whereas the Cl content of biotite from other complexes rarely exceeds 0.1%. Cl-rich biotite is also present in the Vlakkfontein pipes. The F content of most samples of biotite is variable (0–1.1%), and significant heterogeneity exists for major elements as well. However, there is no obvious relationship between major element and halogen contents, and the spectrum of biotite compositions cannot be accounted for by crystal-chemical controls (Munoz 1984).

The compositional variability and Cl-rich nature of the biotite and apatite indicate that Cl-rich fluids were associated with late-stage fractionated melts or high-temperature subsolidus conditions. Such fluids may have been important in processes of PGE transport.

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THE ORIGIN OF THE MERENSKY REEF

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The Merensky Reef occurs at the base of a cyclic unit, one of a series forming the upper part of the Critical Zone of the Complex. There is a generally stepwise decrease in the Sr content of plagioclase between each of the top 3 units of this series. The $\text{Mg}/(\text{Mg} + \text{Fe})$ value of bronzite shows a marked upward decrease in most cyclic units, increasing abruptly again at the base of the overlying unit. Pronounced changes in the Sr initial ratio occur near or within the Merensky unit.

The Ni/Cu and Pt/Cu values of the Merensky reef are 2.3:1 and 5 to 12×10^{-3} , respectively, very

*Speaker.

different from the Ni/Cu and Pt/Cu values of 1.2:1 and 0.1 to 0.25×10^{-3} for the remainder of the Merensky unit. The Bastard unit has a Ni/Cu of 1.2:1 and Pt/Cu of about 0.1×10^{-3} , contrasting with a Ni/Cu of 2 and Pt/Cu of 0.45×10^{-3} in patches of sulfide close to the base of the unit.^{*}

The petrological features demand a model in which PGE enrichment is synchronous with the crystallization of the rocks themselves and argue strongly for successive injection of pulses of new magma. It is proposed that the magma in the intrusion was density-stratified and that new pulses entering the chamber were intermediate in density. Consequently, the new magma rose rapidly as a turbulent plume, drawing within itself and mixing with some of the magma through which it was rising, and spreading out as an intermediate layer.

The high PGE tenor for the sulfides of the Merensky reef is attributed to their early segregation, and thus their very efficient mixing with their host magma, both in the plume and subsequently in the horizontal layer. The Merensky Reef formed once cooling and crystallization caused the density of the new layer to exceed that of the underlying magma, whereupon 'down-spouts' of the dense magma-crystal-sulfide mixture developed and spread out over the chamber floor as the reef.

CRYPTIC COMPOSITIONAL VARIATION IN LAURITE AND ENCLOSING CHROMITE FROM THE BIRD RIVER SILL, MANITOBA

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Cryptic variation in the composition of tens of laurite inclusions in cumulus chromite from chromitite layers of the Bird River Sill provide significant evidence that PGM are trapped during chromite precipitation, and are not exsolved from chromite. Only one laurite grain was found to be postcumulus in about 100 sections. It varies in composition from $(\text{Ru}_{0.96}\text{Ir}_{0.03}\text{Os}_{0.01})\text{S}_2$ to $(\text{Ru}_{0.80}\text{Ir}_{0.04}\text{Os}_{0.16})\text{S}_2$. In general, there is little variation in Ir; within-grain Os-Ru substitution is minor. However, in large grains, strong zonation is evident; $(\text{Ru}_{0.92}\text{Os}_{0.06}\text{Ir}_{0.03})\text{S}_2$ in the core area of one grain ranges to the most Os-rich values. Euhedral laurite, enclosed partly by chromite and partly by an amphibole inclusion, is similarly but less strikingly zoned.

Cryptic variation in chromite compositions is difficult to interpret because of postcumulus modification and a metamorphic overprint. However, the microprobe data show that there are cycles in the Ru-Os substitution in laurite that are related (stratigraphically) to increases in average Ti, Ni, Mg and decreases in Cr and Fe in the host chromite from one chromitite interval. These may relate to episodic additions of new magma, contact metamorphic fluids or both during crystallization of old magma.

PLATINUM-GROUP-ELEMENT RESOURCES IN PODIFORM CHROMITE FROM CALIFORNIA AND OREGON

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Samples from about 280 podiform chromite deposits in California and Oregon were analyzed for Pt, Pd, Rh, Ru and Ir by fire-assay/atomic absorption and spectrographic techniques to estimate by-product PGE potential of chromite mining. The selected deposits feature 1) ophiolites from the Sierra Nevada,

*Speaker.

the Klamath Mountains, the Coast Ranges, and the Canyon Mountain Complex; 2) a Paleozoic to Mesozoic age range; 3) different sizes, shapes, and textures, and 4) variable degrees of superimposed metamorphism. The PGE maximum contents (in ppb) measured for chromitites are: Pt, 2530; Pd, 200; Rh, 140; Ru, 4930; and Ir, 2930. The geometric means for the PGE are 9, 3, 8, 110, and 36 ppb, respectively. Previous studies suggested that relatively few samples can represent the PGE content of a podiform chromite deposit; therefore, these values are assumed to approximate "grades." Tonnage-grade distribution curves were developed for 100 deposits that were sampled for the PGE. The PGE "grade" distribution-curves have the following characteristics:

<u>10% have at least</u>	<u>50% have at least</u>	<u>90% have at least</u>
Pt(ppb) 58	11	2
Pd(ppb) 10	1	0.1
Rh(ppb) 25	6	2
Ru(ppb) 320	120	46
Ir(ppb) 190	39	8

Correlations between Pd and Rh (0.47), Pd and Ru (0.47), Pt and Rh (0.64), Pt and Ir (0.75), Pt and Ru (0.75), Rh and Ir (0.50), Rh and Ru (0.61), and Ir and Ru (0.75) are significant at the 1% level. Chromite production from California and Oregon amounted to about 691,800 tonnes; if the PGE grade distributions are applied to this total production, the mean amounts in kilograms were: Pt 17.7, Pd 3.1, Rh 7.8, Ru 11.2, and Ir 59.1. The low ppb "grades" suggest that very little of the metals could be recovered economically, and mean amounts of metal suggest that the supply of by-product PGE is small.

PLATINUM-GROUP ELEMENTS IN SVECOKARELIAN NICKEL-COPPER OCCURRENCES, FINLAND

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PGE and Au have been analyzed with neutron activation, following preconcentration with nickel sulfide collection and with fire assay, from five Finnish Ni-Cu occurrences (Kotalahti, Vammala, Laukunkangas Hitura and Petolahti) from a layered mafic intrusion in northern Finland (Siika-Kämä) and from several barren or weakly mineralized ultramafic bodies in Lapland. PGE values recalculated to 100% sulfide are slightly higher for Rh, Pt and Pd in the Kotalahti deposit than in Laukunkangas and Vammala, which exhibit the lowest PGE values of the Ni-Cu occurrences analyzed. The ultramafic-hosted Hitura deposit, which exhibits a flat chondrite-normalized distribution pattern of PGE, has concentrations of PGE 20 to 40 times higher than those in Laukunkangas and Vammala. The nickel deposit of Petolahti in a diabase dyke has PGE values close to the level of Hitura, but the Pd/Ir ratio of Hitura (4.7) is much lower than that of Petolahti (58.7). The slope of the PGE distribution pattern of Siika-Kämä is steep, and the deposit has the highest concentrations analyzed in this study, Pt and Pd being up to 656 and 1790 ppm, respectively, recalculated to 100% sulfides. The PGE values of the weakly mineralized ultramafic bodies in Lapland are very low, all well below the values reported from Laukunkangas and Vammala. The data corroborate the idea that the magma/sulfide ratio of the intrusion is the main factor controlling the PGE abundances in the sulfide fraction.

PHASE COMPOSITIONS AND CRYPTIC VARIATION IN A 2.2-KM SECTION OF THE WINDIMURRA LAYERED GABBROIC INTRUSION, YILGARN BLOCK, WESTERN AUSTRALIA: A COMPARISON WITH THE STILLWATER COMPLEX

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The Windimurra Complex is a 2200-km² elliptical Archean (> 2.67 Ga) layered gabbroic intrusion with an estimated thickness of ca. 9 km in the northern Yilgarn Block of Western Australia. Major- and

*Speaker.

trace-element microprobe analyses were undertaken on plagioclase, olivine, augite and hypersthene in a suite of rocks from 2.2 km of stratigraphy at Windimurra Hills toward the east of the intrusion. The phases exhibit a limited mean compositional range throughout the succession: olivine $\text{Fo}_{67} \rightarrow \text{Fo}_{56}$, augite $\text{Wo}_{38.7}\text{En}_{46.4}\text{Fs}_{15.0} \rightarrow \text{Wo}_{46.6}\text{En}_{37.3}\text{Fs}_{16.8}$, hypersthene $\text{Wo}_{2.5}\text{En}_{68.3}\text{Fs}_{29.3} \rightarrow \text{Wo}_{2.9}\text{En}_{63.7}\text{Fs}_{34.0}$, plagioclase $\text{An}_{79} \rightarrow \text{An}_{72}$. Variation in compositions with stratigraphic height is irregular, and the complete range in compositions is locally expressed over the smallest sampling interval. However, there is a trend toward a small amount of iron enrichment in the mafic silicates over the entire sequence.

Trace-element concentrations in the mafic silicates exhibit extensive variability, although selected elements confirm the limited differentiation trend.

Trace Elements in Mafic Silicates, mean $\pm$ std. devn. (wt.%)

	Olivine	Hypersthene	Augite
Ni	0.13 ± 0.05	0.08 ± 0.03	0.07 ± 0.03
Mn	0.35 ± 0.06	0.32 ± 0.04	0.20 ± 0.03
Cr	0.02 ± 0.02	0.05 ± 0.02	0.10 ± 0.04
TiO ₂	—	0.32 ± 0.06	0.51 ± 0.11
Al ₂ O ₃	—	0.59 ± 0.45	1.58 ± 0.91

Comparisons of major- and trace-element data for the Windimurra Hills section with published data for the Stillwater Complex suggest that the Windimurra Hills section can be considered as stratigraphically equivalent to the middle of the Banded Series and as having been derived from a similar but more evolved magma than that from which rocks adjacent to the J-M Reef crystallized.

PLATINUM-GROUP MINERALS IN OPHIOLITE COMPLEXES: AN EXAMPLE FROM SHETLAND

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Conventionally it is thought that platinum-group-element (PGE) minerals in ophiolite complexes contain dominantly Ru, Os and Ir. In the Shetland ophiolite complex, all six are present as discrete mineral phases. Within the scope of our investigation Os-, Ir- and Ru-rich alloys and sulfides have been found included within chromite. In contrast, all six PGE, especially Pt, Pd and Rh, are found as arsenides and antimonides in the silicate phases interstitial to the chromite. The PGE are commonly found in association with each other, forming composite PGE mineral grains and in concentration some two orders of magnitude greater than previously reported.

An ophiolite complex is situated on the islands of Unst and Fetlar in the Shetland Islands. The lower part of the complex is composed of harzburgite and is overlain by dunite, which itself grades up into wehrlite and clinopyroxenite. The uppermost levels of the complex are represented by gabbro intruded at the top by a swarm of dykes. Chromite occurs in lenses of dunite within the harzburgite and in the overlying layered dunite.

β -autoradiography, involving the irradiation of polished thin sections, has been used to locate the PGE minerals. A systematic study of chromite-rich samples has indicated concentrations of PGE minerals within chromite-rich lenses of dunite, themselves within the harzburgite.

The factors concentrating the platinum-group elements include igneous processes and secondary metamorphic-hydrothermal alteration. The association of such elements as Ni, Cu, As, Sb and Co might be useful as tracer elements in the exploration for the PGE.

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A THREE-DIMENSIONAL VIEW OF MINERALIZATION IN THE STILLWATER J-M REEF

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The Stillwater Mining Company has drilled more than 700 core holes spaced less than 15 m apart through the J-M Reef in the Minneapolis Adit area, affording a three-dimensional view of sulfide mineralization. Stratigraphically, mineralization occurs at four levels relative to the base of Olivine-bearing sub-zone I (OB I), which is the lowest occurrence of olivine in the Banded Series: 1) "Footwall" mineralization, found below OB I, is finely banded on a cm-scale, 2) "Basal" mineralization straddles the basal OB I contact, 3) "Main zone" mineralization is near the basal contact but entirely within OB I rocks, and 4) "Upper zone" mineralization is within OB I but well above the basal contact. Basal, Main, and Upper zone mineralization is usually broadly disseminated over a few metres. Most often only one zone is present over any significant strike-length, but up to three stacked zones do occasionally occur. Most of the ore occurs within the Basal and Main zones.

In lateral dimension, Upper zone mineralization occurs sporadically across the entire drilled area. Footwall mineralization is confined to the western portion. Basal and Main zone mineralization occurs as irregular, discrete bodies which, in long section, appear elongate, crescentic, or crudely "doughnut"-shaped. These bodies extend 9 to 45 m in the shortest lateral dimension, and 30 to 120 m in the elongate dimension. The "doughnuts" are 90 to 120 m across, and spaced 120 to 150 m centre to centre. Localization of mineralization does not appear related to depressions in the basal contact of OB I, nor to the thickness of OB I, although structural complications may mask such a relation.

The "doughnuts" of mineralization could result from magmatic convection cells, with solution of sulfides in the hotter, upwelling, central (barren) portion, and precipitation of sulfides along the cooler downfalling periphery. Rayleigh numbers indicate turbulent convection, so that if convection cells do occur, the life of such cells and duration of associated sulfide precipitation and accumulation may be entirely within the time scale of the turbulence.

STRATIGRAPHIC RELATIONS OF THE PGE MINERALIZATION IN THE CENTRAL PALAWAN COMPLEX, PHILIPPINES

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The central part of the Palawan complex is composed predominantly of an ophiolite sequence. The base is a tectonite complex that represents the upper part of the mantle and consists mainly of harzburgite and dunite. These rocks are cut by various dykes and dunite bodies. Above it, there is a thick sequence of layered gabbros, which locally grade downward *via* troctolite into layered dunite. This is overlain by homogeneous gabbro with plagiogranite and hornblende gabbro. The top of the sequence is built up of pillow basalts, which are fed by diabase dykes.

Chromite occurs in four horizons. Chromite of group I, from the tectonite level deep in the ophiolite complex, shows Cr/(Cr + Al) values between 0.78 and 0.95; chromite of group II, from a shallower level, ranges from 0.64 to 0.78, and that of group III, from near the lower contact of the gabbro (cumulates and diapirs) shows a range of 0.5 to 0.64. Group-IV chromite, from the gabbro zone itself, has a value between 0.38 and 0.50.

Small chromite bodies with a thin envelope (type A) show Cr/Fe ratios below 2.5, whereas larger orebodies (type B) have a higher value. In both types the Cr/Fe ratio increases with the chromite/silicate ratio within individual occurrences.

Studies of inclusions in the chromite have proved that PGM together with Ni- and Cu-sulfides only occur in the horizons IA and IIB. By microprobe analysis, laurite, erlichmanite, rutheniridosmine and (probably) IrS₂ were identified.

*Speaker.

GENESIS OF PLATINUM-GROUP ELEMENTS AND GOLD IN A HYDROTHERMAL SULFIDE OCCURRENCE IN A NIPISSING INTRUSION, NORTHEASTERN ONTARIO

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Pt, Pd and Au are concentrated in a small Cu-Ni sulfide occurrence hosted by a Nipissing-type intrusion located near Rathbun Lake in the Lake Wanapitei – Portage Bay area of northeastern Ontario. Unlike most PGE-enriched sulfide deposits, the Rathbun Lake occurrence appears to be of hydrothermal rather than magmatic origin. In the zone of sulfide mineralization, primary silicates in relatively pristine gabbro-norite have been extensively altered by fluids to chlorite, sericite, quartz and biotite. Oxygen isotope analyses indicate that the fluid was at a temperature of 300 to 400°C and at least partly meteoric in origin.

Chalcopyrite and pyrite are the principal sulfides, occurring as massive and disseminated mineralization, and appear to have spatially replaced earlier primary silicates. Gold is evident within pyrite as tiny fracture-fillings and exsolved blebs < 2 µm in size. Bismuthian merenskyite and, to a lesser extent, kotulskite are the Pd-bearing minerals, whereas Pt occurs as sperrylite. Approximately 60% of the Pd mineral grains are associated with altered silicates rather than sulfides. Many of the largest of these form clusters of up to 15 grains. Sperrylite is more intimately associated with sulfides and appears to have formed before the Pd minerals. Although the presence of some PGM grains within sulfides indicates that they may have been exsolved, the size and number of grains associated with silicates suggests that many also were precipitated independently.

In geochemical analyses of samples from the occurrence, no correlation is evident between contents of S and the PGE or Au. Cu averages 9%, Ni 0.5%, Pt 9736 ppb, Pd 20829 ppb and Au 3053 ppb. In contrast to Pt and Pd, values for the other PGE are near background levels. This relative enrichment of Pt and Pd may be typical of hydrothermal PGE deposits and indicates that Os, Ir, Ru and Rh are much less soluble than Pt, Pd and Au. Similar large ratios of (Pt + Pd): (Os + Ir + Ru + Rh) and Cu:Ni have been noted in other PGE-enriched sulfide deposits thought to be of hydrothermal origin.

ANALYSIS OF Pt-ASSOCIATED GRAPHITE BY ACCELERATOR MASS SPECTROMETRY

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It has long been recognized that a minor proportion of PGE in mineralized layered intrusions is spatially related to concentrations of late-stage volatiles, and it is also well known that reduced forms of C are an important if enigmatic component in many types of mineral deposit. Any genetic significance of C–O–H–S fluids and associated volatiles remains unproven in the case of the precious metals, and so we have studied graphite from a pothole pegmatite of the UCZ of the western Bushveld, and from the J–M/Howland Reef of the Stillwater.

Graphite habits include coarsely crystalline, massive, globular, spheroidal shells and delicate filaments, ranging from the millimetre to the micrometre scale. In order to study the chemistry of the graphite in more detail we have employed the sensitive technique of Accelerator Mass Spectrometry (AMS). We have collected semiquantitative 'milliprobe' AMS data for Bushveld graphite B13-19/2 and Stillwater graphite C3AV. Both samples contain coarse (maximum lath-size 2 mm, largest aggregate 4 mm) crystalline graphite; the Stillwater material in particular is (in terms of appearance and C₁H₁O secondary-ion currents), close to the purest (Sri Lankan vein) natural graphite we have analyzed to date. These grains of graphite appear much coarser, more crystalline and purer than 'graphite' we have seen from carbonaceous Au deposits. Mass spectra collected over the mass range 1–260 AMU and charge states (q values of –1, +2 to +6) have allowed recognition of trace elements to the sub-ppm level, in the absence of interfering molecular species.

Results show that, compared with the vein graphite, both samples have much higher trace-element

*Speaker.

concentrations, which appear to be contained within the graphite itself, or within possible inclusions therein. Both samples have elevated levels of Cl (also observed by electron microprobe), and low F/Cl relative to analyzed samples from Au mines and graphite deposits. The Stillwater sample also has significant levels of S and Cu. Our data on the Stillwater material are consistent with the presence of Pt at the ppm level.

POTENTIAL FOR PLATINUM-GROUP ELEMENTS IN THE FOX RIVER SILL, NORTHEASTERN MANITOBA

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The Fox River Sill is a major stratiform intrusion of Proterozoic age that forms an integral part of the Fox River Belt of northeastern Manitoba. The westernmost segment of the intrusion, which has been examined in detail, is subdivided into a marginal zone (MZ), lower and upper central layered zones (LCLZ, UCLZ) and a hybrid, partly granophyric roof-zone (HRZ). Each zone is characterized by distinctive cyclic arrangement of units. The Sill is predominantly ultramafic in composition, more than 75% (by volume) of the intrusion being composed of olivine-rich olivine cumulate rocks. An estimated minimum of 70 layers that form 35 cyclic units make up the western part of the intrusion.

The LCLZ is composed of a simple succession of cyclic units, each consisting of a thick dunite layer overlain by a thin olivine clinopyroxenite layer. Plagioclase and orthopyroxene are rare, as are sulfide minerals. The UCLZ succession is composed of relatively thin cyclic units of variable composition. Orthopyroxene and plagioclase are common, and sulfide minerals, which are common accessories, are locally abundant (up to 10%).

The dramatic change in the character of the main layered succession at the LCLZ-UCLZ contact represents a significant event in the magmatic history of the intrusion. The change in composition of the cyclic units implies a change in composition of the magma that produced the UCLZ cyclic units. Mixing of some of the overlying residual magma-column with fresh batches of magma may be a contributing factor. The presence of locally abundant magmatic sulfides in cyclic units above the contact is considered especially noteworthy. Their association with UCLZ orthopyroxene- and plagioclase-bearing orthocumulates suggests that these zones of disseminated sulfides may be potentially significant for concentrations of PGE, by analogy with platiniferous horizons in other major stratiform intrusions.

Sr AND Nd ISOTOPE EVIDENCE FOR PRESERVED DENSITY-STRATIFICATION IN THE MAIN ZONE OF THE BUSHVELD COMPLEX: IMPLICATIONS FOR THE ORIGIN OF THE MERENSKY REEF AND UNDISCOVERED PGE MINERALIZATION IN THE UPPER ZONE

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The Bushveld Complex is the product of fractional crystallization of two magma series and their mixtures in a density-stratified magma chamber. The series, termed U and A to reflect their Ultramafic and Anorthositic products, respectively, have distinctive compositions. The U magmas give olivine boninite with SiO₂ 52–56%, MgO 12–16%, Cr > 1000 ppm, high incompatible-element contents, a (⁸⁷Sr/⁸⁶Sr)₂₀₅₀ (R_o) ratio between 0.703 and 0.705, and εNd/εSr co-ordinates close to those of Bulk Earth. A magmas are tholeiitic in composition, with R_o ~ 0.709 and εNd/εSr values that indicate extensive crustal contamination.

Sr isotopic compositions of the U and A series are so different that the chronology of magma intrusion into the Complex can be tracked by means of R_o of the layered cumulates. The bulk of the 3-km-thick Main zone is isotopically distinct from the underlying Critical zone, the rocks that lie above the "Pyroxenite marker", and the chilled gabbroic marginal rocks that occur along the basal margin of the Complex. The Main zone is interpreted as a "fossilized" layer of high-R_o A liquid with low PGE contents that

*Speaker.

intruded into a stratified pile of liquid dominated by A + U mixtures of the Upper Critical zone (R_o 0.7065) near the base of the chamber at a level consistent with its density.

Beneath the new liquid layer, downward mixing occurred with 400 m of trapped liquid that had very different composition, temperature, $f(O_2)$ and sulfur content and high contents of PGE, causing a rapid change in R_o and giving rise to the Merensky Reef. More substantial mixing with the superelevated magma-column at the top of the sheet produced an R_o reversal at the "Pyroxenite marker". The composition of the magma column above the "Pyroxenite marker" was changed by mixing with liquid residual from fractionation of the Main zone, which increased its R_o to ~ 0.7073 . Because this magma packet was enriched in PGE, and because minor precious-metal mineralization is known in the Upper zone, undiscovered PGE ore deposits are postulated above the "Pyroxenite marker".

PRECIOUS-METAL AND RARE-EARTH CONCENTRATIONS OF BUSHVELD PERIDOTITE SILLS: INDICATORS OF MAGMATIC PGE CONTENTS

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Sills and irregular bodies of poikilitic harzburgite occur throughout the Bushveld Complex. They are most abundant along the basal margin of the Complex in the Burgersfort region (East Transvaal), where they intrude rocks of the Transvaal Sequence. They cut across layered Lower zone rocks 60 km north of Burgersfort and Upper Critical zone rocks in the Loskop Dam area.

All Bushveld sills are LREE-enriched ($Ce_N/Yb_N \sim 8-12$). Three types can be identified by the Sr isotope and mineral compositions and precious-metal concentrations: 1) Burgersfort type: ($^{87}Sr/^{86}Sr$)₂₀₅₀ (R_o) 0.703–0.705, Pt 30–40, Pd 10–20, Ir 1–2 ppb. 2) Stroomrivier type: low PGE (Pd 8 ppb). 3) Loskop type: R_o is 0.708, similar to Lower Main zone rocks, and PGE are very high (Pd 180 ppb).

The geochemistry of the sills can be simulated by mixing olivine and orthopyroxene phenocrysts with liquids akin to quench-textured micropyxenites (olivine boninites: U-type). The phenocryst/matrix equilibria in the Burgersfort and Loskop types indicate that the sills did not crystallize from peridotitic liquids. An origin by sweeping crystals and then parental layers of magma from the floor of the chamber is proposed. The matrices of the phenocryst-bearing sills represent a continuous sample of parental Bushveld magmas.

Addition of A-type liquid of tholeiitic composition diluted the U characteristics and increased R_o , but the concentration of PGE continued to increase in the residual magmas. The matrix of the Loskop sills that sample the pre-Merensky Reef Upper Critical zone ($Pd_{liq} \sim 300$ ppb) is enriched relative to the more primitive Burgersfort sills from the lower zone ($Pd_{liq} \sim 40$ ppb). This argues that the UG-2 and Merensky Reef PGE mineralization has an internal (evolved) rather than external (new magma) origin.

PLATINUM-GROUP-ELEMENT-BEARING INCLUSIONS IN CHROMITE OF THE ULTRAMAFIC ZONE, STILLWATER COMPLEX, MONTANA: OCCURRENCE, CHEMISTRY, AND PETROLOGICAL SIGNIFICANCE

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The presence of platinum-group-element-bearing phases in many parts (*i.e.*, Ultramafic and Banded zones) of the Stillwater Complex has been documented by many investigators. For this study, we have

*Speaker.

petrographically and geochemically examined PGE-bearing phases that occur as inclusions in chromite from the chromitite seams in the Ultramafic zone. The areas of the Complex examined in detail are Mountain View, Benbow, and West Fork.

The PGE-bearing inclusions are present in both disseminated and massive chromite, but are modally more abundant in massive chromite. They are small, generally less than 15 μm in diameter, and characterized by a euhedral to subhedral habit. Their distribution is random (not crystallographically controlled) within the chromite host. Although polyphase silicate (anhydrous and hydrous) $\pm$ base-metal sulfide (BMS) inclusions are common to many chromitite seams (A through K horizons) of the Ultramafic zone (and J-M Reef), the PGE-bearing phases occur as solitary inclusions in chromite. Thus far, all identified PGE-bearing inclusions are sulfides of Ru, Os and Ir (e.g., laurite, RuS_2). The $\text{Ru}/(\text{Ru} + \text{Os} + \text{Ir})$ (Ru#) ratio ranges from 0.84 to 0.93, with $\text{Ru} \approx \text{Os}$ solid solution more extensive than $\text{Ru} \approx \text{Ir}$. Both Pd and Rh abundances are less than 2 weight %. No Pt has been detected. At present, the chemical data do not indicate a correlation between stratigraphic height and Ru#, nor between chromite composition and Ru#.

Whole-rock PGE concentrations in the chromitites range from a few ppb to nearly 16 ppm, with $\text{Pd} > \text{Pt} > \text{Rh} > \text{Ir}$ (Os was not analyzed). This is almost opposite to the data for the inclusions, which show high Ru, Ir and Os, low Rh and Pd, and no detectable Pt.

Thus in the Stillwater magma chamber, Ru, Ir and Os precipitated early, possibly as high-temperature alloys, and were included in chromite. In contrast, Pd, Pt and Rh remained in solution in the magma; they are present in phases that precipitated late, i.e., interstitial to chromite. These data, for the first time, shed light on the fractionation pattern of the PGE.

A KEY DIAGRAM FOR THE OPTICAL DETERMINATION OF PLATINUM-GROUP MINERALS

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A key diagram for the routine optical investigation of platinum-group minerals has, for the first time, been developed on the basis of the most recent reflectance and microhardness data. The diagram contains 65 minerals, which occupy defined fields representing the entire range of R and VHN values.

The minerals of different PGE have been identified by special colors. In addition, cubic (isotropic) minerals can be distinguished. The vertical extension of the fields is based mainly on the intensity of bireflectance (R_1 - R_2), but also in part on chemical variations.

A large proportion of the minerals occupy easily distinguishable fields. Considering isotropy, anisotropy and intensity of bireflectance, they can be identified optically. Identification of minerals whose fields partly overlap also becomes possible by using other standard wavelength or reflectance curves as further discriminating criteria.

PLATINUM-GROUP ELEMENTS IN THE BIRD RIVER SILL

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The Bird River Sill is a layered mafic-ultramafic intrusive complex of Archean age in southeastern Manitoba. Petrographic and petrochemical investigations have been conducted on polished slabs, thin sections and rock powders. Microprobe and ore microscopy investigations are in progress.

Concentrations of up to 700 ppb combined Pt and Pd were obtained from several different layers in the ultramafic portion of the sill. There is a pronounced positive correlation between the high Pt and Pd values and base-metal sulfides. This suggests that the base-metal sulfides were important collectors of Pt and Pd. In addition, Pt and Pd are, to a lesser degree, also collected in a rock layer enriched in chrome spinel; however, this unit represents a distinctive turbulent phase within the depositional history of the sill.

Petrographic and petrochemical studies suggest a complex intrusive history, characterized by multiple injections of differentiating magma punctuated by episodes of magma supersaturation, resulting in layers of skeletal olivine separated by undisturbed cumulate crystal portions. Episodes of violent magmatic

*Speaker.

turbulence are evidenced by disrupted rock-layers including dunite, chromitite and sulfide-rich "pebbles". Lateral inhomogenities in the magma chamber are evidenced by differences in the crystallization sequence between the eastern and the western section that cannot be explained by tectonic disruption.

Chondrite-normalized patterns of platinum-group-element distribution show a steep positive slope from Os to Pd characteristic of gabbro-related deposits. The strong depletion of Pt in samples from the upper parts of the ultramafic sequence is considered to be an indication of a Pt depletion in the injected magma. Current studies focus on a correlation of platinum-group-element mineralization with the composition, injection and crystallization history of the magma.

PGE IN THE 3.6-GA BON ACCORD Ni-Fe-Co-Cr OCCURRENCE, BARBERTON, SOUTH AFRICA: IMPLICATIONS FOR CRUST-MANTLE-CORE SEGREGATION

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The Bon Accord deposit occurs as a boudin in deformed, greenschist- to amphibolite-facies metamorphosed ultramafic rocks of the Komati Formation, Barberton. Whole-rock samples were analyzed for PGE, REE and Pb- and Nd-isotope compositions. Chondrite-normalized PGE plots define an asymmetric field from slightly enriched chondritic values with consistent positive Ru and Rh anomalies to an extremely depleted high-temperature PGE concentration. This field does *NOT* bear any relationship to the deformation and metamorphism of the deposit and reflects pre-emplacement chemistry.

A hydrothermal or Fe-meteorite origin are unlikely because: 1. The Cr-spinel compositions are similar to those found in chromitite from a layered complex in the ultramafic host-rock. 2. Field mapping suggests that the host rocks were part of an extensive sheet of altered alpine-type peridotite, with high background Ni, Co and Cr. 3. REE concentrations are higher than chondritic; Au values are chondritic and Sb and Co/Cr values are very high compared to any meteorites. 4. Preliminary Pb-isotope studies indicate that present-day Pb isotopic ratios are unusually radiogenic for whole-rock samples of this nature. Modeling is compatible with an age equivalent to the host rock.

The depleted values of the high-melting-point PGE are similar to those in chromitites from ophiolites and layered complexes thought to be derived from upper-mantle sources. The depleted to chondritic values in the Bon Accord occurrence suggests that the geodynamic processes that led to formation of a 2-layer mantle-reservoir system were not completed by mid-Archean. Evidently, simatic crust of this age tapped one reservoir mantle-source. Local heterogeneities like Bon Accord may represent a siderophile segregation that was not incorporated into the outer core, or was tectonically dismembered from the mantle-core transition zone.

THE BEHAVIOR OF THE PGE AND Au DURING PARTIAL MELTING AND FRACTIONAL CRYSTALLIZATION: EVIDENCE FROM MAGMAS ON THE KAAPVAAL CRATON

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An attempt is made to identify upper mantle - crust processes that produced various PGE patterns observed in a suite of volcanic and hypabyssal rocks from the Kaapvaal Craton. The rock types vary from komatiites to tholeiites and span the period 3.2 to 1.8 Ga.

*Speaker.

The observed trends suggest that Pt, Pd and Au are the most incompatible PGE in mantle minerals. Os, Ir, Ru and Rh are retained to a greater degree in the mantle residue during partial melting, as refractory phases. The MgO content of the magmas is related to PGE content. Pt increases with increasing MgO to a maximum at 12% MgO, then flattens out and may decrease. Pd appears more incompatible than Pt, reaching a maximum value at lower MgO values. Ir shows low values at low to intermediate MgO, with a logarithmic increase in the ultramafic end-members. The production of tholeiitic melts would result in "differentiated" liquids (high Pt/Ir ratios and steeply positive trends) whereas komatiites have low Pt/Ir ratios and flattish trends.

The differences in refractory behavior also control the PGE during fractional crystallization. The association of Ir (and from this study Ru, Os and Rh) with olivine and chromite is well documented. Probably only Rh enters the crystal lattices of these minerals to any significant extent. The others are probably present as high-temperature sulfides (*e.g.*, laurite) or alloys that should crystallize before the first oxides and silicates could serve as nucleation seeds. The removal of Ir, Os, Ru and Rh with early cumulates therefore reflects a temperature, rather than chemical, control. In sulfur-undersaturated melts, the PGE (most notably Pt and Pd) and Au would accumulate in the residual liquid. The presence of an immiscible sulfide phase would override these considerations owing to the chalcophile nature of the PGE and Au.

POTHOLE STRUCTURES: UNDERGROUND TELEVISION FOOTAGE FROM FOUR PLATINUM MINES

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Ore-filled transgressive features in the otherwise conformable footwall units of platinum ore "reefs" have become generically referred to as *potholes*. The specific morphology of these generally circular pothole features is categorized in a companion abstract in this program.

The apparent localization of these features to the Merensky Reef and UG-2 platiniferous chromitite horizons in the Bushveld Igneous Complex, South Africa, suggests that they are critically involved in PGM petrogenesis. Until now, only three published papers and the 1981 Bushveld Excursion Guidebook have given any specific details of pothole structures in the Bushveld Complex.

Bushveld-type potholes are suspected in some anomalous zones exposed in exploration drifts in the Stillwater Complex, Montana. Transgressive or offlapped footwall units do suggest pothole-like depressions, but the ore-value horizon has not yet been proven to drape into these footwall structures.

With the generous assistance of the geological staffs and their company managers, television videotape coverage of cross-sectional data and actual pothole structures on ore horizons of the following mines are presented: in Africa, Impala Platinum (Gencor), Rustenburg Platinum (Johannesburg Consolidated Investment Company), and Western Platinum Ltd.; in the U.S.A., the Stillwater Mining Company (Trivenure). This TV tape covers some of the mining methods and a number of different types of pothole contacts and settings.

*Speaker.

EXAMPLES OF Pd–Pt MINERALIZATION ALONG THE 35-KM STRIKE OF THE STILLWATER REEF, MONTANA

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The recent discovery of extensive graphite–PGE mineralization in pegmatites stratigraphically below the main palladium–platinum reef at Stillwater (Volborth & Housley 1984) emphasizes the need for a detailed investigation of the ore mineralogy of the reef. Cores from several deep drill-holes covering 35 km of lateral extent have, accordingly, been selected for a pilot study, the first results of which are presented in this communication.

Several factors emerge that affect the nature of the PGM association; these include the nature of the host rock, texture and composition of base-metal sulfides, the intensity of metamorphism and serpentinization, and the extent of hydrothermal effects. The presence of graphite and chlorine, and the proximity to diabase dykes, pegmatites and pipe-like bodies, are also relevant in this context.

Exceptionally large grains of PGM such as vysotskite, braggite, cooperite, moncheite, michenerite, sperrylite, kotulskite, guanglinite, isoferroplatinum, keithconnite, merenskyite and some others have been selected for detailed optical and microprobe studies. New analyses and corresponding reflectance and microhardness data of these minerals are presented. The significance of volatile phases for the mineralizing processes and certain similarities with the Merensky Reef of the Bushveld Complex are considered.

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PLATINUM–CHROMITITE ASSOCIATION IN THE BUSHVELD COMPLEX

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The association of platinum-group elements (PGE) with the chromitite layers of the Upper Critical zone of the Bushveld Complex is well established. Analytical data for Pt and Pd of several of the chromitite layers shows most of these to have their own characteristic composition. For the chromitite layers of the middle group, for instance, Pt + Pd values are generally below 1 ppm in the MG–1 layer; MG–2 is characterized by a Pt/Pd $\approx$ 3.0 and Pt + Pd $\approx$ 1.6 ppm; for MG–3 the Pt + Pd content is about the same, although the Pt/Pd ratio is lower ($\approx$ 1.85), whereas the MG–4 layer is characterized by slightly lower values ($\approx$ 1.0) but the highest Pt/Pd ratio of $\approx$ 4.0. This pattern for the MG chromitite layers is consistent for more than 70 km along strike in the western Bushveld and consequently reflects changes in the PGE ratios of the magma from which these layers crystallized. Calculations indicate that, except for the Merensky Reef, a much larger volume of magma is required for the formation of the chromitite layers than for the associated PGE mineralization. These features, as well as absolute PGE concentrations, distribution of PGE values within the chromitite layers and the positioning of the mineralized layers and their associated lithologies within the stratigraphic column, are evaluated in terms of density stratification in magma chambers and magma-mixing models.

*Speaker.

PLATINUM-GROUP MINERALS FROM CHROMITITE IN ALPINE-TYPE PERIDOTITE OF THE CACHE CREEK GROUP, BRITISH COLUMBIA**PETER J. WHITTAKER****Ontario Geological Survey, 77 Grenville Street, Toronto, Ontario M5S 1B3***DAVID H. WATKINSON***Ottawa-Carleton Centre for Geoscience Studies, Carleton University, Ottawa, Ontario K1S 5B6*

Platinum-group minerals (PGM) are most commonly found in chromitites with massive, podiform and nodular textures. Chromitites themselves are hosted by tectonized harzburgites, parts of dismembered ophiolites. PGM are subhedral to euhedral, 5 to 10 μm in size, and occur in both altered and unaltered parts of chromite. Distribution of PGM inclusions is irregular. Individual grains of chromite host PGM inclusions from positions near their edges to their centres and exhibit no crystallographic control over habit or position of inclusions.

PGM inclusions often occur in conjunction with the Ni-Fe sulfide pentlandite. Sulfides are anhedral and occur in variable proportions to the PGM, but are always subordinate in volume. PGM and PGM-sulfide inclusions may also occur with an anhedral silicate, thought to be clinopyroxene.

PGM in alpine-type chromitites are Ru-rich members of the laurite (RuS_2) - erlichmanite (OsS_2) solid-solution series. From Cache Creek Group samples, they are slightly more Os-rich than similar inclusions from other ophiolitic terranes. Where intersected by altered fractures in chromite, PGM have as much as 4 wt. % As and a mottled texture. This suggests susceptibility to alteration during serpentinization.

Entrapment of a primary Ni-Fe-PGE sulfide during chromite growth with later exsolution is suggested. The two resulting phases are laurite and pentlandite, with euhedral laurite the first to form.

PLATINUM-GROUP-ELEMENT CONCENTRATIONS IN ROCKS NEAR THE BASE OF THE STILLWATER COMPLEX, MONTANA**MICHAEL L. ZIENTEK****U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025, U.S.A.***LEUNG MEI***U.S. Geological Survey, 923 National Center, Reston, Virginia 22092, U.S.A.*

Sulfide mineralization near the base of the Stillwater Complex, a layered ultramafic to mafic intrusion in southwestern Montana, occurs in the Basal series of the complex and in Stillwater-associated sills and dykes that intrude metasedimentary rocks in the contact aureole. The Basal series consists of a Basal bronzite cumulate zone (bbc; bronzite cumulates) overlying a Basal norite zone (bno; bronzite $\pm$ plagioclase $\pm$ olivine $\pm$ augite cumulates). Based on field and petrological studies, five distinct magma-types are represented in the sill and dyke suite: gabbro-norite (Grp 1), high-Mg gabbro-norite (Grp 2), mafic norite (Grp 3), high-Ti norite (Grp 4), and olivine gabbro (Grp 6).

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Concentrations of Pt, Pd and Rh have been determined for samples from these groups and from the Peridotite zone (upd). The results are:

unit	number of samples analyzed	number of samples at or below detection limit(*) (Pd,Pt,Rh)	50% have at least (Pd,Pt,Rh) in ppb	10% have at least (Pd,Pt,Rh) in ppb	median Pd/Pt
upd	37	7,16,27	2.8,2.2,*	2.1,8,1.6	1.3
bbc	5	4,5,5	*,*,*	1,7,*,*	
bno	58	1,12,29	13.9,9.2,1.1	34,22,7	1.5
Grp 1	40	7,8,33	7,5,*	140,100,100	1.4
Grp 2	5	2,2,3	4.3,2.8,*	22,19,5	1.5
Grp 3	20	3,8,13	12,3,*	87,18,9	4
Grp 6	4	4,3,4	*,*,*	*,3,*	

Concentrations of Pt, Pd and Rh were all below detection limits (2, 1 and 1 ppb respectively) for two samples of high-Ti norite. These values are typical for basaltic magmas but are about an order of magnitude less than for samples from the marginal rocks of the Bushveld Complex.