Discrimination between Magmatic and Hydrothermal Ni-Cu-PGE and PGE Mineralization

C. M. Lesher and **R.R. Keays**
Mineral Exploration Research Centre, Department of Earth Sciences, Laurentian University, Sudbury, ON P3E 6B5, Canada
e-mail: lesher@sympatico.ca

Introduction

Mafic-ultramafic-hosted Ni-Cu-(PGE) and PGE deposits are believed to have formed by segregation of immiscible sulfide melts and/or alloys from mafic-ultramafic magmas in dynamic magmatic systems such as lava channels, feeder dikes, and magma chambers. However, some of the mineralization in some deposits (e.g., hydrothermal veins at Kambalda: Lesher & Keays, 1984; Stillwater J-M reef: Boudreau et al., 1986; Sudbury footwall ores: Farrow & Watkinson, 1996) is associated with hydrous and/or halogen-bearing phases and is interpreted to have formed from or been modified by hydrothermal fluids.

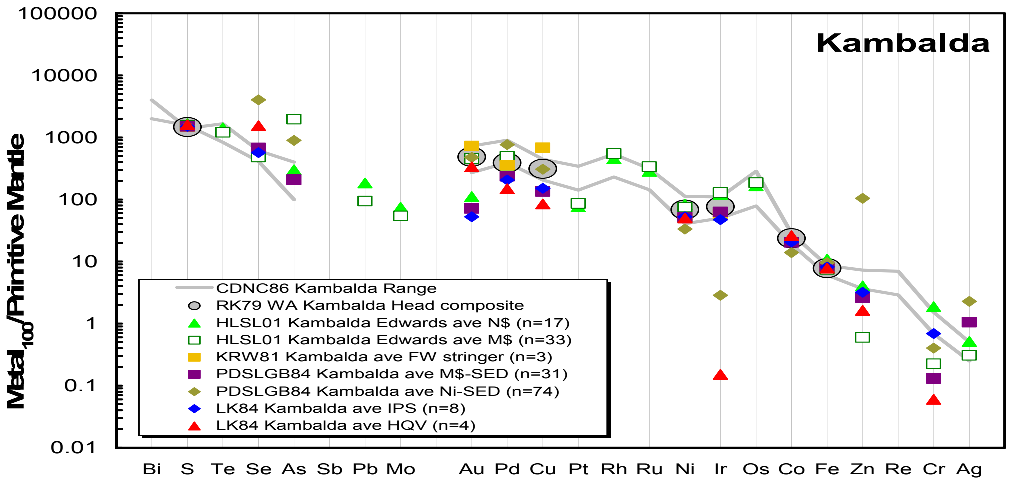
Different base, precious, and semi-metals have different solubilities and partition differently between silicate magmas, sulfide melts, and supercritical fluids/volatiles (e.g., Keays & Crocket, 1970; Keays et al., 1982; Barnes & Maier, 1999; Mathez, 1999; Wood, in press). For example, the solubilities of Fe, Co, Ni, Cu, PGEs, and Au are different in sulfide melts and hydrothermal fluids; Au, Cu, and platinum-group PGEs (PPGE: Pt, Pd, Rh) behave differently than Ni, Co, and iridium-group PGEs (IPGE: Ru, Ir, Os); and Ru and Ir behave differently than other IPGEs. Therefore, it should be possible to distinguish between those ores deposited by magmatic processes and only modified by hydrothermal fluids and those ores deposited directly from hydrothermal fluids. Unfortunately, very few deposits have been systematically analyzed for complete suites of base, precious, and semi-metals, but it is possible to make some preliminary interpretations.

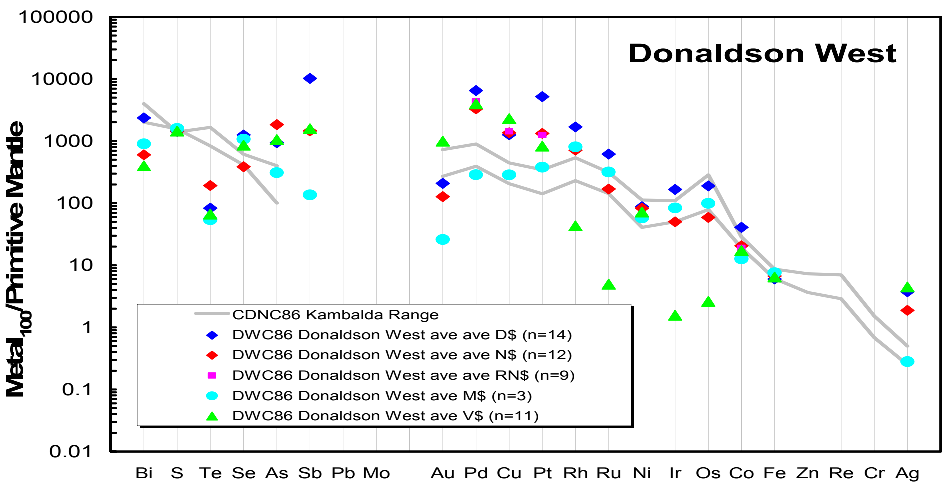
Discrimination

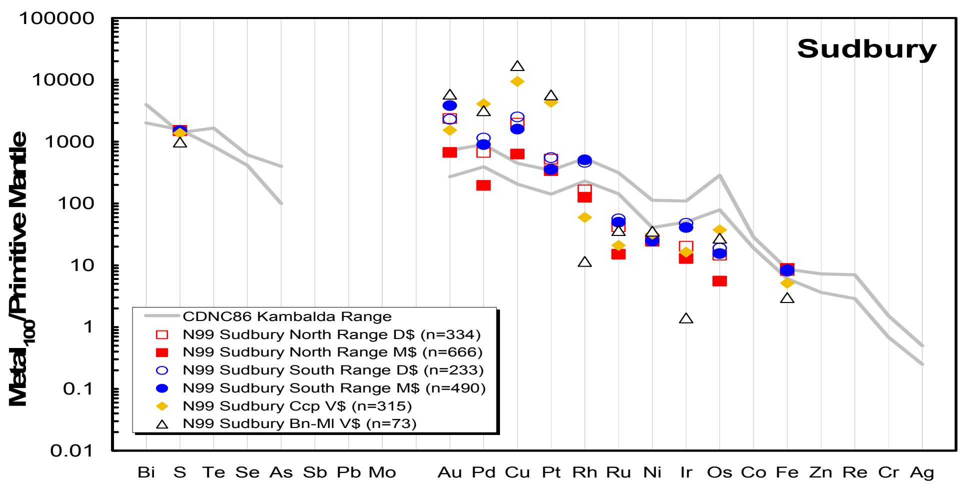
Although the behavior of the different metals varies with magma/fluid composition, temperature, pressure, fO_2, and fS_2, the general order of partitioning into sulfide melts appears to be PGE ~ Au > Cu > Ni > Co > Fe, whereas the general order of solubility in hydrothermal fluids appears to be Fe > Cu ~ Au > Pt ~ Pd > Ni > Co >> Ru ~ Ir. Differential crystallization/ precipitation processes can further fractionate different elements, but it is possible, at least in most cases, to distinguish between magmatic and hydrothermal mineralization on the basis of Au/Cu/Pt/Pd, Ir/Ni, and Cr/Fe ratios. These differences are best illustrated on primitive mantle-normalized variation diagrams (Figs. 1-5; data sources shown as initials of authors and year; ore types: D$ = disseminated, N$ = net-textured, RN$ = reverse net-textured, M$ = massive, IPS = Interpillow, Ni-SED = Ni-enriched metasedimentary, V$ = hydrothermal vein.)

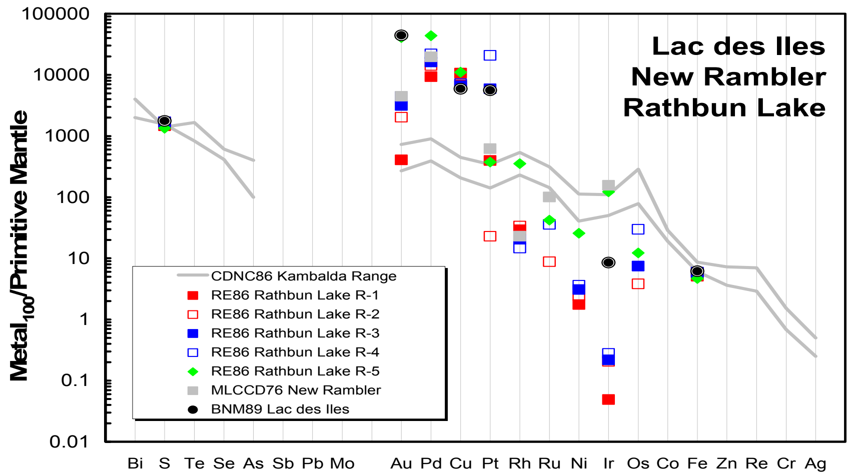
For example, the majority of the ores at Kambalda (Fig. 1), Langmuir (not shown), Donaldson West (Fig. 2), and Sudbury (Fig. 3) exhibit relatively systematic variations in metal ratios with fractionations consistent with magmatic segregation from komatiitic, basaltic komatiitic, and noritic magmas (see Barnes & Naldrett, 1985), respectively, and local mobilization of Au, Pd, Pt, and/or Cu. However, hydrothermal veins and Ni-enriched metasediments in these localities are strongly depleted in Ir, sometimes depleted in other IPGE (e.g., Rh at Sudbury, Rh-Ru-Os at Donaldson), and also depleted (where data are available) in Cr. In contrast, ores at Lac des Iles, New Rambler, and Rathbun Lake (Fig. 4) are strongly enriched in PPGE relative to IPGE and strongly depleted in Ir relative to Ni and/or other PGE. Their compositions are consistent with hydrothermal modification of magmatic sulfides (Lac des Iles and some Rathbun Lake samples) or with hydrothermal transport and deposition (New Rambler and some Rathbun Lake samples).

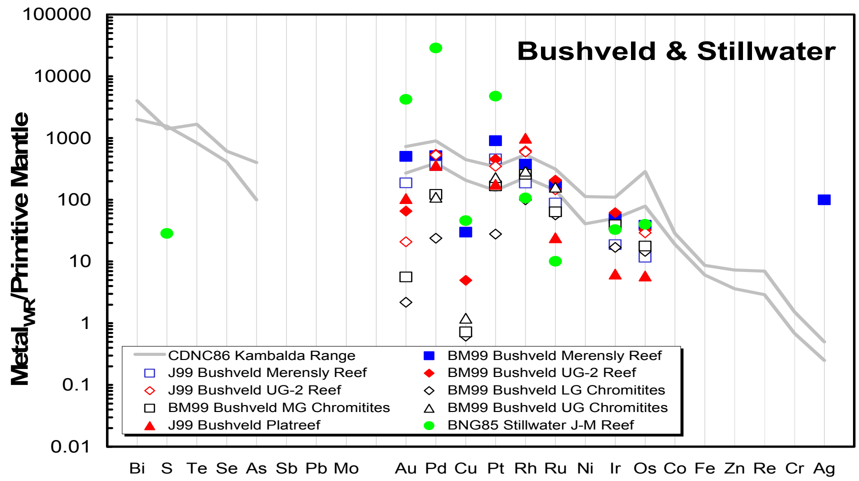
The ores in the Bushveld and Stillwater complexes (Fig. 5) are depleted in Ni and Cu relative to other metals, but are not significantly depleted in Ir or other IPGE. Their Ir contents are more consistent with magmatic segregation (e.g., Campbell et al., 1983) and hydrothermal modification than with hydrothermal generation (e.g., Boudreau et al., 1986). However, Stillwater ores appear to have lower Cu and much higher Pd and Pt contents, consistent with stronger hydrothermal modification.


Kambalda
Metal100/Primitive Mantle
100000
10000
1000
100
10
1
0.1
0.01
CDNC86 Kambalda Range
RK79 WA Kambalda Head composite
HLSL01 Kambalda Edwards ave N$ (n=17)
HLSL01 Kambalda Edwards ave M$ (n=33)
KRW81 Kambalda ave FW stringer (n=3)
PDSLGB84 Kambalda ave M$-SED (n=31)
PDSLGB84 Kambalda ave Ni-SED (n=74)
LK84 Kambalda ave IPS (n=8)
LK84 Kambalda ave HQV (n=4)
Bi S Te Se As Sb Pb Mo Au Pd Cu Pt Rh Ru Ni Ir Os Co Fe Zn Re Cr Ag


Donaldson West
Metal100/Primitive Mantle
100000
10000
1000
100
10
1
0.1
0.01
CDNC86 Kambalda Range
DWC86 Donaldson West ave ave D$ (n=14)
DWC86 Donaldson West ave ave N$ (n=12)
DWC86 Donaldson West ave ave RN$ (n=9)
DWC86 Donaldson West ave M$ (n=3)
DWC86 Donaldson West ave V$ (n=11)
Bi S Te Se As Sb Pb Mo Au Pd Cu Pt Rh Ru Ni Ir Os Co Fe Zn Re Cr Ag


Sudbury
Metal100/Primitive Mantle
100000
10000
1000
100
10
1
0.1
0.01
CDNC86 Kambalda Range
N99 Sudbury North Range D$ (n=334)
N99 Sudbury North Range M$ (n=666)
N99 Sudbury South Range D$ (n=233)
N99 Sudbury South Range M$ (n=490)
N99 Sudbury Ccp V$ (n=315)
N99 Sudbury Bn-MI V$ (n=73)
Bi S Te Se As Sb Pb Mo Au Pd Cu Pt Rh Ru Ni Ir Os Co Fe Zn Re Cr Ag





Clearly, more experimental data are required to establish the relative mobilities of PGEs in hydrothermal fluids, but if the observed fractionations in known hydrothermal ores are characteristic, then they suggest that the PGE mineralization in the Bushveld and Stillwater Complexes *segregated* via magmatic processes and was subsequently *modified* by hydrothermal processes.

References

Barnes, S.-J., and Maier, W.D., 1999, The fractionation of Ni, Cu, and the noble metals in silicate and sulphide liquids *in* Dynamic Processes in Magmatic Ore Deposits and their Application to Mineral Exploration, GAC Short Course Notes, v. 13, p. 69-106.

Barnes, S.-J., Naldrett, A.J., and Gorton, M.P., 1985, The origin of the fractionation of the platinum-group elements in terrestrial magmas, Chem. Geol., v. 53, p. 303-323.

Boudreau, A.E., Mathez, E.A., and McCallum, I.S., 1986, Halogen geochemistry of the Stillwater and Bushveld Complexes: Evidence for transport of the platinum-group elements by Cl-rich fluids, J. Pet., v. 27, p. 967-986.

Brügmann, G.E., Naldrett, A.J., and Macdonald, A.J., 1989, Magma mixing and constitution zone refining in the Lac des Iles Complex, Ontario; genesis of platinum-group element mineralization, Econ. Geol., v. 84, p.1557-1573.

Campbell, I.H., Naldrett, A.J., and Barnes, S.J., 1983, A model for the origin of platinum-rich sulphide horizons in the Bushveld and Stillwater Complexes, J. Pet., v.24, p. 133-165.

Cowden, A., Donaldson, M.J., Naldrett, A.J., and Campbell, I.H., 1986, Platinum-group elements and gold in the komatiite-hosted Fe-Ni-Cu sulfide deposits at Kambalda, Western Australia, Econ. Geol., v. 81, p. 1226-1235.

Dillon-Leitch, H.C.H., Watkinson, D.H., and Coats, C.J.A., 1986, Distribution of platinum-group elements in the Donaldson West deposit, Cape Smith Belt, Québec, Econ. Geol., v. , 81, p. 1147-1158.

Farrow, C.E.G., and Watkinson, D.H., 1996, Geochemical evolution of the Epidote Zone, Fraser Mine, Sudbury: Ni-Cu-PGE remobilization by saline fluids, Expl. Min. Geol., v. 5, p. 17-31.

Green, A.H., and Naldrett, A.J., 1981, The Langmuir volcanic peridotite-associated nickel sulphide deposits, Econ. Geol., v. 76, p. 1503-1523.

Heath, C., Lahaye, Y., Stone, W.E., and Lambert, D.D., 2001, Origin of variations in nickel tenor along the strike of the Edwards Lode nickel sulfide orebody, Kambalda, Western Australia, Can. Min., v. 39, p. 655-672.

Jones, R.T., 1999, Platinum Smelting in South Africa (http://www.mintek.ac.za/Pyromet/Platinum/Platinum.htm)

Keays, R. R. and Crocket, J. H., 1970, A study of the precious metals in the Sudbury nickel irruptive ores: Econ. Geol., v. 65, 438-450.

Keays, R.R., Nickel, E.H., Groves, D.I. and McGoldrick, P.J., 1982, Iridium and palladium as discriminants of volcanic exhalative, hydrothermal, and magmatic nickel sulfide mineralization, Econ. Geol., v. 77, p. 1535-1547.

Keays, R.R., Ross, J.R., and Woolrich P., 1981, Precious metals in volcanic peridotite-associated nickel sulfide deposits in Western Australia, II: Distribution within ores and host rocks at Kambalda, Econ. Geol., v. 76, p. 1645-1674.

Lesher, C.M., and Keays, R.R., 1984, Metamorphically and hydrothermally mobilized Fe-Ni-Cu sulphides at Kambalda, Western Australia, *in* Buchanan, D.L., and Jones, M.J. (Eds.), Sulphide Deposits in Mafic and Ultramafic Rocks, Inst. Min. Metall., London, p. 62-69.

Mathez, E.A., 1999, Factors controlling the concentrations of platinum-group elements in layered intrusions and chromitites, *in* Dynamic Processes in Magmatic Ore Deposits and their Application to Mineral Exploration, GAC Short Course Notes, v. 13, p. 251-286.

McCallum, M.E., Loucks, R.R., Carlson, R.R., Cooley, E.F., and Doerge, T.A., 1976, Platinum metals associated with hydrothermal copper ores of the New Rambler mine, Medicine Bow Mountains, Wyoming, Econ. Geol. v.71, p.1429-1450.

Naldrett, A.J., Asif, M., Schandl, E., Searcy, T., Morrison, G.G., Binney, W.P., and Moore, C, 1999, Platinum-group elements in the Sudbury ores; significance with respect to the origin of different ore zones and to the exploration for footwall orebodies, Econ. Geol, v. 94, p.185-210.

Paterson, H.L., Donaldson, M.J., Smith, R.N., Lenard, M.F., Gresham, J.J., Boyack D.J., and Keays, R.R., 1984, Nickeliferous sediments and sediment-associated nickel ores at Kambalda, Western Australia, *in* Buchanan, D.L., and Jones, M.J. (Eds.), Sulphide Deposits in Mafic and Ultramafic Rocks, Inst. Min. Metall.,, London, p. 81-94.

Ross, J.R., and Keays, R.R., 1979, Precious metals in volcanic-type nickel sulfide deposits in Western Australia: I. Relationships with the composition of the ores and host rocks, Can. Min., v. 17, p. 417-436.

Rowell, W.F, and Edgar, A.D., 1986, Platinum-group element mineralization in a hydrothermal Cu-Ni sulfide occurrence, Rathbun Lake, northeastern Ontario, Econ. Geol, v. 81, p.1272-1277.

Wood, S.A, in press, The aqueous geochemistry of the platinum-group elements with applications to ore deposits, *in* Cabri, A. (Ed.), The Geology, Geochemistry, Mineralogy, and Mineral Beneficiation of the Platinum-Group Elements, Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 54.