Current Approaches for the Process Mineralogy of Platinum-Group Element Ores and Tailings

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ABSTRACT

Characterisation of platinum-group element (PGE) deposits and their process products has many challenges for the process or applied mineralogist. It is now well established that the PGE distribution for such samples is variably divided between submicroscopic concentrations of PGE in sulfides, tellurides and related minerals occurring as discrete platinum-group minerals (PGM), of which there are a large number of species, many with partial replacement between the PGE and between anions. Each PGE deposit type requires a targeted approach but fundamentally, there are two general methodologies in vogue. One way is to make a large number of polished or polished thin sections for detailed scanning electron microscopy (SEM)/optical examination to determine the PGM distribution and their associations and grain sizes. The other is to make concentrates of representative crushed or processed samples, thus having fewer subsamples to examine. Our method of choice is to use hydroseparation (HS) for concentration. HS provides representative concentrates of sizes down to ~10 µm, not possible by other techniques. Various microbeam methods have been used for analysis of trace quantities of PGE (EPMA, micro-PIXE, SIMS and LAM-ICPMS). We prefer LAM-ICPMS (laser ablation microprobe – inductively coupled mass spectrometry) because of the relatively large analytical volume sampled, the ability to measure all the PGE, monitor up to 20 elements, together with detection levels in the tens to a few hundreds of ppb. We provide typical results derived in studies of stratiform PGE ores and tailings, and a massive Ni-Cu sulfide ore.

INTRODUCTION

Characterisation of platinum-group elements

The low tenor of platinum-group elements (PGE) in ores, together with their usual occurrence as very small inclusions of platinum-group minerals (PGM), which often show complex chemical replacements, make their characterisation difficult. Because the PGE are chalcophile in addition to being siderophile, they also occur submicroscopically in major sulfide minerals, and this is the reason why their characterisation has lagged behind that of most other mineral groups. Additionally, a veil of secrecy has prevailed until the 1970s on the mineralogy, geochemistry and geology of the PGE (Cabri, 1981a). For example, the first published account of platinum (from alluvial deposits in the Chocó district, Colombia), was based on the journals of Don Antonio de Ulloa in 1748 (McDonald and Hunt, 1982). About 260 years later, at the time of the discovery of the world-famous Bushveld PGE deposits in 1924, only about eight PGM were known (Cabri, 1981b). Hence, characterisation of the PGE needed advances in microscopic analytical techniques, of which the most important is the electron microprobe, whose application to PGM was pioneered by Soviet scientists in 1959 (eg publications by A D Genkin and co-workers) so that by 2002 there were 109 known PGM species (Cabri, 2002) even though detailed X-ray crystallographic data at that time were only known for 5.6 per cent of the PGM.

The second important development was applying techniques for analysis of trace quantities of PGE in major minerals, such as sulfides. Cabri (1992) reports on our knowledge at that time using electron probe microanalysis (EPMA) with levels of detection (LOD) of about 300 - 500 ppm, microparticle induced X-ray excitation (micro-PIXE) with LOD for Pd, Rh and Ru of <10 ppm (eg Cabri *et al*, 2002). More recent developments have applied instrumentation with lower LOD, such as secondary ion mass spectrometry (SIMS) with LOD <1 ppm for all PGE, eg Oberthür *et al* (1997), and laser ablation microprobe ICP mass spectrometry (LAM-ICPMS) with LOD of tens ppb for all PGE, eg Cabri *et al* (2003).

Process mineralogy of platinum-group elements

A review of sample preparation techniques for PGE-bearing materials stresses the need for samples that are large enough to be representative, sample homogeneity, and the need for preconcentration to achieve useful results (Cabri, 1981c). It is with this background that the process mineralogist plans to study ores and metallurgical products. The preconcentration task and efficiency of preconcentration has been greatly advanced by the invention and application of a non-toxic technology to concentrate minerals, which is called hydroseparation or HS by Rudashevsky *et al* (2002). This technology is directly applicable to PGE-bearing materials because of its efficiency at concentrating representative aliquots of fine-grained minerals, in contrast to what is possible with conventional techniques such as heavy liquids, where it was demonstrated that recovery of sperrylite (D = 10.8 g/cm^3) in a synthetic mixture of purified pyrrhotite, chalcopyrite and pentlandite (D = 4.6, 4.2 and 4.96 g/cm^3, respectively) dropped off from 80 - 100 per cent at +106 -150 µm to ten to 12 per cent at +45 -54 µm (Cabri, 1981c). Unfortunately, there are laboratories today that either do not preconcentrate, or do not use the most efficient techniques for preconcentration.

CASE STUDIES

Metallurgical samples from Merensky Reef

An 868 g sample of flotation tailings from the Merensky Reef, Bushveld, South Africa (Table 1) was studied using HS concentration and SEM examination. The sample was sized at 45, 75, 125 and 180 µm to produce a heavy mineral concentrate for each size fraction. The most common sulfide and oxide species, often found associated with PGM, but also as liberated particles, are chalcopyrite, magnetite, pentlandite, monoclinic pyrrhotite and troilite. Less common was arsenopyrite, galena, ilmenite and chromite. Troilite was found to be pure FeS, based on 7 EPMA, but monoclinic pyrrhotite contains a little Ni with an average composition of $(Fe_{6.96}Ni_{0.04})S_{7.99}$ (n = 5).

The pentlandite was also analysed for trace Pd, using wavelength dispersion EPMA at 30 kV, 200 nA and 150 s and in one case using EDS at 30 kV, 170 s. The detection level was estimated to be 50 ppm under the former conditions and 1500 ppm in the latter (for the highest value measured). The average content of pentlandite, based on 17 analyses, is 407 ppm Pd with a wide range from the detection level (50 ppm) to 3300 ppm.

A total of 83 separate PGM grains were found in this tailing sample, which were distributed as 2354 separate particles. Five

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TABLE 1

Assay data for two Bushveld tailing samples.

Element	Flotation tails	
	Merensky	UG-2
Au (g/t)	0.24	
Pt (g/t)	0.68	0.68
Pd (g/t)	0.44	0.48
Cu (%)	<0.05	<0.05
Cr (%)	2.33	20.2
Ni (%)	0.13	0.11
S (%)	0.11	0.01

PGM were found, listed in order of volumetric abundance are: tetraferroplatinum (89.5 per cent), laurite (7.7 per cent), isoferroplatinum (2.6 per cent), an unknown mineral, possibly new $(Pt,Pd)Fe_3$ (0.1 per cent), and PdCu (<0.1 per cent), a then unknown Pd-Cu alloy, now known as skaergaardite (Rudashevsky *et al*, 2004). The average composition of tetraferroplatinum was found to be $Fe_{0.99}(Fe_{0.80}Cu_{0.16}Ni_{0.05})$ based on 58 EPMA. The average composition of isoferroplatinum was determined to be $Pt_{2.63}Fe_{1.29}Cu_{0.71}Ni_{0.02}$ based on eight EPMA. However, confirmation of the latter mineral requires X-ray diffraction analysis. EPMA analyses of the six liberated grains of laurite gave $(Ru_{0.79}Os_{0.07}Ir_{0.04}Fe_{0.09})S_{2.00}$ and $(Pd_{0.95}Pt_{0.05})(Cu_{0.57}Sn_{0.16}Fe_{0.09}As_{0.06}Pb_{0.04}Cr_{0.04}Ni_{0.02}Au_{0.02})$ for two analyses of the PdCu alloy, which is probably the new mineral skaergaardite.

A few of the PGM are shown in Figure 1 to illustrate the dominance of fine-grained intergrowths, dominantly associated

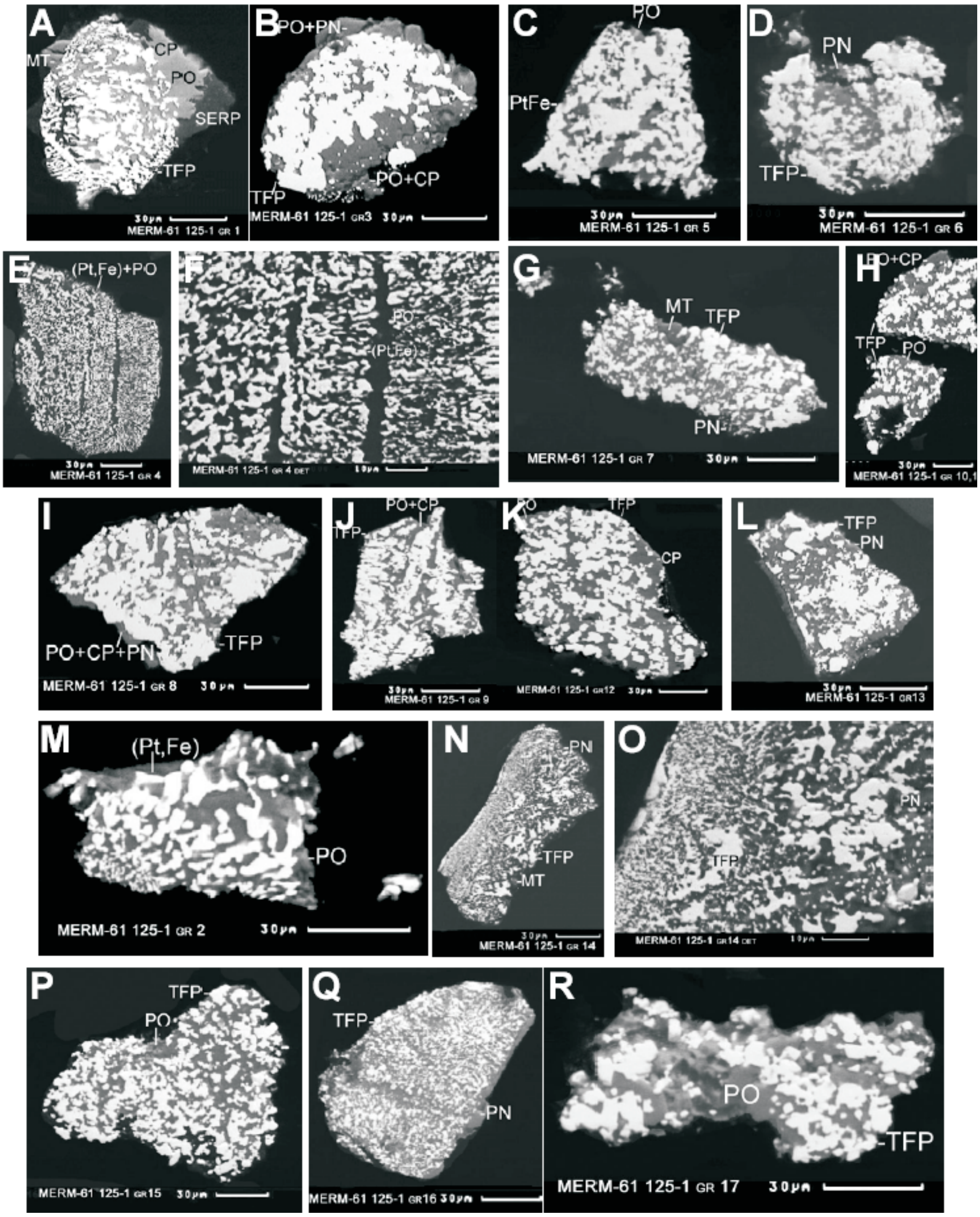

FIG 1 - Pt-Fe alloys intergrowths with sulfides (B, C, D, E, F, H, I, J, K, L, M, 0, P, Q, R) and with sulfides and gangue (A, G, N). Abbreviations are: TFP = tetraferroplatinum; (Pt,Fe) = probably isoferroplatinum; po = pyrrhotite; pn = pentlandite; cp = chalcopyrite; mt = magnetite; serp = serpentine.

with sulfides (65.9 vol per cent), followed by PGM attached to gangue (12.6 vol per cent), attached to both sulfide and gangue (10.8 vol per cent), free (9.0 vol per cent) and included in gangue (1.7 vol per cent). Interestingly, all six laurite grains found are free and account for 86 vol per cent of the 13 free PGM.

The mineralogical investigation shows that the bulk of the Pt content is contained in two Pt-Fe alloys: tetraferroplatinum and isoferroplatinum and that the Pd content is represented largely as a solid solution in pentlandite, estimated to be about 400 ppm Pd on average, though it ranges widely from about less than 50 to 3300 ppm.

The Pt-Fe alloys are characterised by occurring as fine-grained graphic intergrowths with sulfides (mostly pyrrhotite/troilite and pentlandite) or with magnetite. Though the area of each Pt-Fe particle was measured to arrive at total volume and mass Pt values, it is not realistic to calculate a grain-size distribution because it is likely that each measured inclusion forms part of a larger interconnected grain under the polished section surface. Suffice to note that the majority of Pt-Fe alloy particles were found in the 45 - 75 and the 75 - 125 µm size fractions, with one large particle in the 125 - 180 µm fraction and eight in the -45 µm fraction. Free laurite particles occur with an average ECD of 47.8 µm (range 33.7 - 59.9 µm).

The following tentative conclusions may be made with respect to mineral processing, though these conclusions are speculative because there is no information on the mineralogy of this particular head sample prior to the flotation tests used to produce the tail. Therefore, one might speculate that flotation was not effective in collecting the Pt-Fe alloys and their intergrowths, or in collecting laurite. Because no Pt-Pd arsenides, sulfides or tellurides were found, which are common in the Merensky reef, it may further be surmised that flotation was indeed very effective at concentrating these PGM.

It may also be noted that there is traditionally less interest in concentrating laurite (the principal carrier of Ru, and probably also of Ir and Os) from the industry's point of view due to the relatively low demand for Ru and Ir, and especially for Os. However, the latest accounting of sales shows that the Ru price increased 293 per cent from 2006 to 2007, by far the highest increase of the PGE in that period that ranged from ten to 38 per cent (Johnson Matthey, 2007). Ruthenium is an essential material in the manufacture of a new type of hard disk which uses perpendicular magnetic recording, or PMR. These first took significant market share in 2006 and 2007 has seen continued growth with almost 40 per cent of production now being PMR technology, compared to 15 per cent in 2006.

For this particular tailings sample, it may be further suggested that magnetic separation will concentrate most of the ferromagnetic Pt-Fe alloys, together with a significant proportion of the pentlandite and monoclinic pyrrhotite. This will increase recovery of Pt, Pd and Ni.

Metallurgical samples from Merensky Reef

The senior author was subcontracted with the task of providing trace PGE analyses of the major sulfide minerals for a large geometallurgical study of the Merensky Reef that was done for Impala Platinum Mines Limited. The work was divided into two subprojects, the focus on the first being trace PGE analyses of sulfides using LAM-ICPMS, based on 63 particles preselected by SGS Lakefield Research Limited, with most preanalysed by electron microprobe: 32 hexagonal pyrrhotite, six troilite, 16 pentlandite, seven pyrite and two chalcopyrite. Some selected particles consisted of intergrowths of hexagonal pyrrhotite and troilite. In those cases, the predominant mineral composition was used for calibration calculations. In the second subproject, the focus was to analyse 25 preselected pyrrhotite particles for Pt only by SIMS.

LAM-ICP-MS analyses of Ru, Rh, Pd, Ir, Pt and Au in sulfides

A total of 191 LAM-ICP-MS analyses were carried on selected areas of pentlandite, pyrrhotite, chalcopyrite and pyrite (Figure 2), in addition to 51 of pyrrhotite standards (CANMET po-41 and po-31), using the older HP4500 ICP-MS instrument coupled to a NUWAVE UP213 nm NdYAG laser at Memorial University of Newfoundland. Twenty-five isotopes were monitored, of which quantitative data were obtained for ^{101}Ru, ^{102}Ru, ^{103}Rh, ^{105}Pd, ^{106}Pd, ^{108}Pd, ^{191}Ir, ^{193}Ir, ^{194}Pt, ^{195}Pt and ^{197}Au. The results are given in Table 2 for a total of 137 acceptable analyses (77 per cent) after careful examination of the depth profiles for subsurface inclusions (PGM or other minerals) and corrections made for argide interferences (Sylvester, 2001). Typical depth profiles are shown in Figure 3.

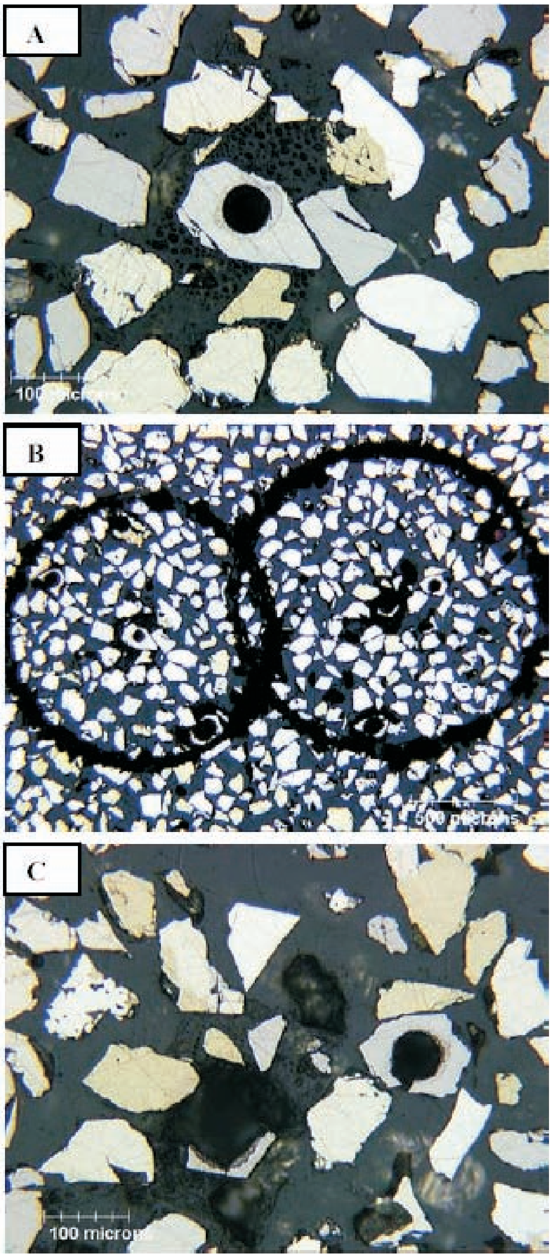

FIG 2 - (A) Is a pyrrhotite particle, (B) shows several sulfides within each circle that have been analysed, (C) shows a remnant of an analysed pyrrhotite particle (just below the centre) and a particle later confirmed to be pyrrhotite to the right of centre. Scale bar in (A) and (C) is 100 µm and 500 µm in (B).

TABLE 2

Summary of PGE and Au analyses of sulfides (ppm).

Mineral	Ru	Rh	Pd	Ir	Pt	Au
Pentlandite (n = 17)	10.224 (1.287 - 25.567)	35.362 (0 - 228.885)	225.724 (0.366 - 554.899)	2.238 (0 - 4.646)	3.255 (0 - 7.743)	0
Pyrite (n = 40)	40.049 (0 - 879.965)	55.944 (0 - 778.685)	84.443 (0 - 465.749)	6.451 (0 - 76.453)	3.354 (0 - 49.637)	0.012 (0 - 0.158)
'Pyrrhotite' (n = 51)	2.851 (0 - 29.219)	(0.475) (0 - 5.836)	0.035 (0 - 1.479)	1.219 (0 - 5.539)	0.979 (0 - 11.901)	0.017 (0 - 0.288)
Troilite (n = 5)	N/A (0 - 1.300)	N/A (0 - 0.801)	0	0.351 (0 - 0.862)	0	0
Chalcopyrite (n = 24)	0.048 (0 - 1.160)	0	0.016 (0 - 0.388)	0.005 (0.005)	0.043 (0 - 0.686)	0

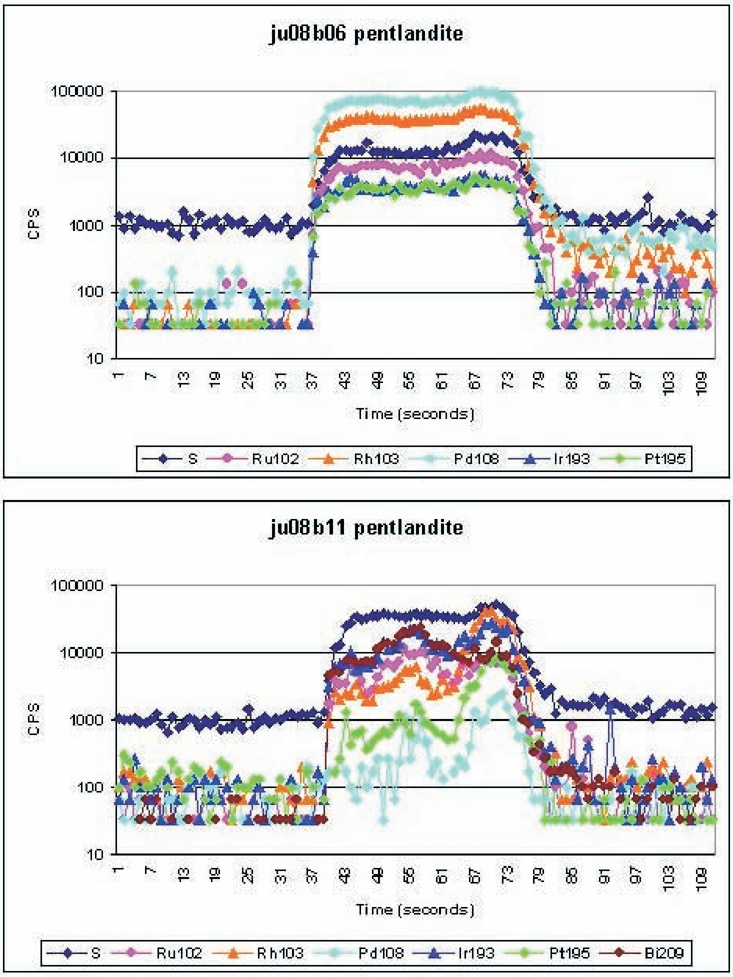

FIG 3 - The upper spectrum shows a homogenous PGE distribution in pentlandite over the whole depth profile with concentrations (ppm): Ru 25.567; Rh 31.534; Pd 280.127; Ir 1.789; Pt 3.745). The lower spectrum of pentlandite shows spikes of several PGE suggesting inclusions, some of which seem associated with Bi. Therefore, this analysis was not used.

It was concluded that pentlandite, pyrite and pyrrhotite are all carriers of Ru, Rh, Pd, Ir and Pt; most probably as solid solutions in their respective crystal structures. Troilite carries little PGE, most likely only traces of Ir, and chalcopyrite was found to contain traces of Ru, Pd, Ir and Pt at average levels of the order of less than 50 ppb (0.050 ppm). The PGE concentration, when present, appears to be most homogeneously distributed in pentlandite, whereas pyrite often showed an inhomogeneous distribution with depth. The data are considered to be on the conservative side, but an element of uncertainty remains because of analysis of some pyrrhotite particles without preselection.

SIMS analyses of Pt in pyrrhotite

Using a polished section provided by SGS Lakefield Research Limited, 25 SIMS depth profiles were made. It was found that 48 per cent of the analyses were below the limit of detection of 0.29 ppm Pt, and the rest ranged to a high value of 4.232 ppm Pt. An average concentration is not calculated because the analyses are too few and the distribution is far from normal (Figure 4). These results on the deportment of Pt in pyrrhotite compare favourably with the earlier study done on a subsample using LAM-ICPMS (Table 2), and are also comparable to published

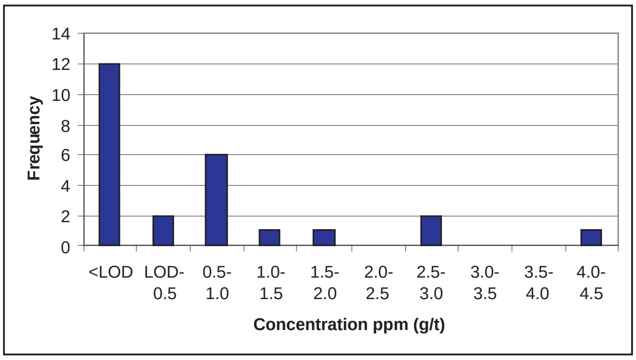

FIG 4 - Frequency distribution of SIMS analyses for Pt concentrations in 25 pyrrhotite particles.

data on the Merensky reef and the Main Sulfide Zone, Great Dyke, Zimbabwe.

In addition to the depth profiles, ion images of ^{198}Pt in two particles with the highest Pt concentrations showed the presence of micro-inclusions of Pt minerals, probably less than 5 µm in diameter. It is concluded that high Pt values are due either to using data containing microinclusions or in other studies that used the voltage-offset method, possibly to analytical problems that may arise in SIMS analyses.

It was recommended that future analyses should be carefully prescreened to distinguish between PGE-poor troilite and pyrrhotite. Additionally, it was suggested that better statistical data should be obtained, such as when analysing a larger number of particles (>100), preferably by LAM-ICPMS in order to provide complete data on all the PGE and for easier evaluation of the influence of subsurface inclusions.

Ni-Cu sulfide PGE-bearing ore

The senior author was subcontracted with the task of providing trace PGE analyses of the major sulfide minerals in a large geometallurgical study for a major Russian Ni-PGE producer. This was part of a flow sheet re-development program to find ways of better rejecting pyrrhotite while maintaining Ni and PGE recoveries.

The goals of the investigation were to determine trace concentrations of rhodium, palladium, platinum and gold in pyrrhotite, pentlandite and cobaltite (which turned out to be pyrite) from concentrates in three polished sections prepared by the client. The trace element analyses were done using laser ablation microprobe inductively coupled plasma mass spectrometry (LAM-ICPMS) on pyrrhotite, pentlandite and pyrite particles. The analyses were done in three days of beam time at Memorial University of Newfoundland over 14 separate analytical sessions for a total of 210 analyses of unknowns of which 200 were accepted, in addition to 84 analyses of two standards (CANMET po-689 and po-41). The analytical system is a Finnigan ELEMENT XR, a high resolution double focusing magnetic sector inductively coupled plasma mass spectrometer (HR-ICPMS), and a GEOLAS 193 nm excimer laser system. Ablations were performed with an argon-fluorine gas laser emitting at the 193 nm wavelength. The average levels of detection were (ppm): Rh (0.010), ^{105}Pd (0.080), ^{106}Pd (0.337), ^{108}Pd (0.195), ^{194}Pt (0.014), ^{195}Pt (0.013) and Au (0.013). After corrections were applied for possible argide interferences on Rh and the 3 Pd isotopes (Sylvester, 2001), the 3 Pd values were examined with respect to the run detection level for the isotope. Where all three or two values were above the limits of detections, the data were averaged. Similarly, if both Pt isotopes were above detection levels, the values were averaged.

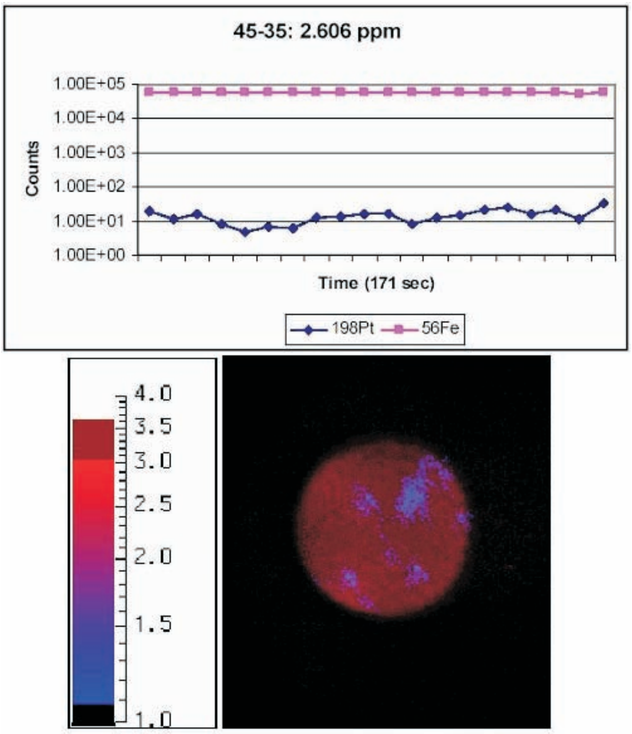

FIG 5 - Upper part shows the depth profile for a pyrrhotite with a relatively regular count rate of 14.9 counts, whereas the lower ion image shows evidence of micro-inclusions of a Pt-bearing mineral where ^{198}Pt (blue) is overlaid with ^{56}Fe (red).

Trace Rh, Pd, Pt and Au were measured in all three minerals, but about nine per cent of the depth profiles of 189 accepted pyrrhotite analyses show evidence of some subsurface inclusions of gold, PGM, as well as other minerals. To obtain data for the pyrrhotite matrix measured intervals were selected by avoiding obvious subsurface inclusions of platinum-group minerals (PGM) and gold. The average precious metal concentrations of pyrrhotite analyses are (ppm): sample 1 Rh 0.748 (δ 0.694; range from not detected to 4.297), Pd 0.127 (δ 0.344; range from not detected to 2.134), Pt 0.142 (δ 0.256; range from not detected to 1.586) and Au 0.033 (δ 0.040; range from not detected to 0.163); sample 2 Rh 0.864 (δ 0.786; range from not detected to 3.702), Pd 0.096 (δ 0.136; range from not detected to 0.444), Pt 0.082 (δ 0.071; range from not detected to 0.345), and Au 0.156 (δ 0.109; range from not detected to 0.611); and sample 3 Rh 1.534 (δ 1.476; range from 0.046 to 8.723), Pd 0.181 (δ 0.392; range from not detected to 2.579), Pt 0.128 (δ 0.122; range from not detected to 0.638) and Au 0.108 (δ 0.092; range from not detected to 0.485). Two pyrrhotite depth profiles are shown in Figure 6, the upper spectrum shows a typical pyrrhotite analysis (1.555 ppm Rh and 0.154 ppm Pt), whereas the lower spectrum shows a complex Pd-Au-Pb-Pt-Sn-Te inclusion(s) outside the selected interval, which has no Rh or Pt, but instead 1.173 ppm Pd and 0.061 ppm Au. In contrast to what was found in other deposits (eg Merensky Reef), there was no significant difference in trace PGE concentrations for the different pyrrhotite polymorphs. The results are summarised in Table 3.

Fewer pentlandite (nine) and only one pyrite analyses were possible due to sparse suitable particles so that the results are not statistically valid. However, pentlandite from all three samples contains Rh, Pd, Pt and Au. The depth profile shown in Figure 7 has concentrations (ppm) of 0.030 Rh, 22.714 Pd, 3.081 Pt and 0.028 Au, the highest Pt determined in this series of analyses. The range of concentrations is largest for Pd in pentlandite, ranging from a low of 9.151 to 563.474 ppm Pd (Table 4).

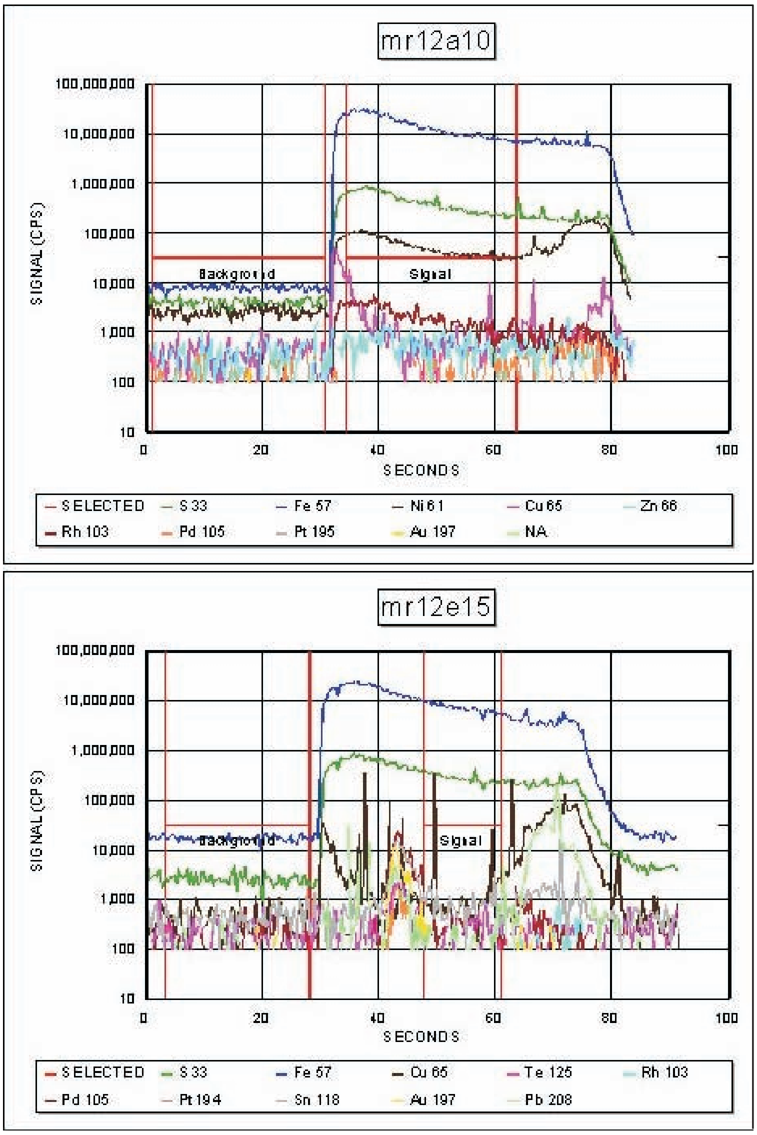

FIG 6 - Two depth profiles of pyrrhotite: the upper one is a typical pyrrhotite analysis and the lower one shows complex multi-element inclusion(s). The vertical orange lines show selected intervals.

TABLE 3

Summary of PGE and Au analyses of pyrrhotite (ppm).

Sample 1 (n = 68)	**Rh**	**Pd**	**Pt**	**Au**
Avg	0.748	0.127	0.142	0.033
Std dev	0.694	0.344	0.257	0.039
Max	4.197	2.134	1.586	0.163
Min	0.000	0.000	0.000	0.000
Sample 2 (n = 67)	**Rh**	**Pd**	**Pt**	**Au**
Avg	0.864	0.096	0.082	0.156
Std dev	0.786	0.136	0.071	0.109
Max	3.702	0.444	0.345	0.611
Min	0.052	0.000	0.000	0.000
Sample 3 (n = 54)	**Rh**	**Pd**	**Pt**	**Au**
Avg	1.534	0.181	0.128	0.108
Std dev	1.476	0.392	0.122	0.092
Max	8.723	2.579	0.638	0.485
Min	0.046	0.000	0.000	0.000

UG-2 tailings sample

A 861 g sample of flotation tailings from the UG-2, Bushveld, South Africa (Table 1) was studied using HS concentration and SEM examination. The sample was sized at 45, 75, 125 and 180 μm to produce a heavy mineral concentrate in each size fraction. The heavy mineral concentrates consisted mainly of chromite, some magnetite and lots of particles from the crushing. No sulfide- chromite association was observed and rare particles of pyrrhotite and pentlandite were found. Ten pentlandite particles were analysed for trace Pd using wavelength dispersion EPMA at 30 kV, 200 nA and 150 s and averaged 262 ppm Pd (<50 to 1330 ppm).

Very few PGM were found in this sample as shown in Figure 8. Four relatively large free particles of subhedral to anhedral laurite were found, ranging in size from 21.9 to 35.0 μm in ECD (Figures 8a, 8b, 8d and 8e). Two grains of Pd minerals were found, the largest being sobolevskite (ideally PdBi), attached to a larger particle of orthopyroxene. The other is kotulskite (ideally PdTe), which occurs as a very small inclusion (3.8 μm) in an unknown telluride that may have a formula of $(Cu,Ag)_2(Te,Se)$, which itself is attached to a much larger particle of chromite (Figure 8h). Only two Pt minerals were

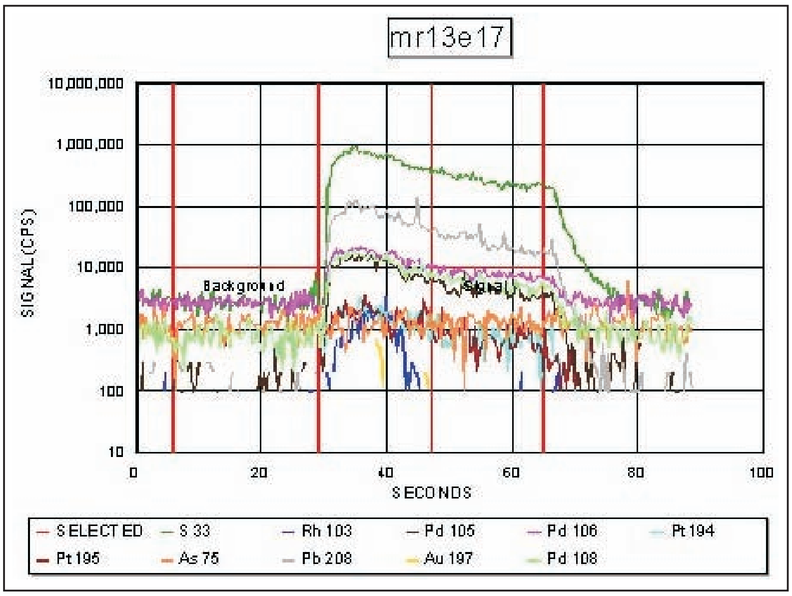

FIG 7 - A pentlandite depth profile that shows a high Pt concentration and a possible Rh-bearing inclusion. The vertical orange lines show selected intervals.

TABLE 4

Pentlandite and pyrite analyses in ppm (Sample 1).

File number		Rh	Pd	Pt	Au	Comments
mr13a04	04	1.662	43.348	2.988	0.255	Pentlandite
mr13a05	05	0.024	98.960	0.061	0.059	Pentlandite
mr13a06	06	0.177	36.375	1.105	0.112	Pentlandite
mr13a07	07	0.229	563.474	0.075	0.054	Pentlandite
mr13a08	08	2.017	9.151	0.496	0.073	Pentlandite
mr13a10	10	0.032	55.965	0.034	0.020	Pentlandite
mr13a11	11	0.013	580.470	0.000	0.138	Pentlandite
mr13a12	12	0.662	20.801	2.413	0.062	Pentlandite
mr13a09	09	0.505	0.460	0.314	0.061	Pyrite

found, both being Pt-Fe alloys. In one case, a small 7.9 µm inclusion (probably isoferroplatinum) is included in pentlandite (Figure 8f) and in the other case; tetraferroplatinum is graphically intergrown with pyrrhotite (Figure 8i).

Though few PGM were found in this sample (possibly because an older model hydroseparator was used, the HS-02M), the data suggest that the Pt occurs as Pt-Fe alloys closely associated with sulfides and that the bulk of the Pd is present in solid solution in pentlandite. The close association with sulfides of Pt and Pd points to the need for improved sulfide recovery. The very small free laurite particles are interesting, but were not the main focus of improving PGE recovery.

CONCLUSIONS

The examples show the effectiveness of using hydroseparation to preconcentrate minerals of interest, especially PGM, in a few polished sections. This provides the process mineralogist with a method that is both cost-effective and efficient. Because crushing and sizing of samples is so crucial to getting good HS results, the application of electric pulse disaggregation or EPD (described recently by Cabri *et al*, 2008) is attracting interest. Recent examples of this approach have been reported by Oberthür *et al* (2007) and Zaccarini *et al* (2008). In the first example a 676 g sample from the Driekop platinum pipe (Bushveld Complex, South Africa) was processed by means of combined EPD and HS technology (Oberthür *et al*, 2007). Half this sample had previously been studied in nine polished sections under optical microscopy and SEM, which resulted in seven polished sections without any PGM grains. One polished section contained two grains of sperrylite (20 and 50 µm) and the second contained seven PGM grains forming a group (area 3 × 5 mm) of particles partly associated with sulfides, whereas over 500 PGM were found in a few polished sections after EPD and HS. In the second example, about 300 PGM grains, ranging between 20 and 120 µm in size, have been found by SEM after EPD processing, sieving and HS concentration of chromitites containing up to more than 2 ppm total PGE from the Loma Peguera ophiolite (Dominican Republic). Some of these PGM and a PGE-bearing sulfide are being characterised in detail as they may be new minerals.

The use of LAM-ICPMS for trace analyses of precious metals, including PGE, is the method of choice for several reasons, especially when compared to another sensitive technique (SIMS). The advantages of LAM-ICPMS over SIMS are the ability to measure/monitor a large number of isotopes (usually 20) in each analysis, lower levels of detection and the sampling of a larger volume. For example, SIMS analyses are commonly done using a 60 µm diameter area at an ablation rate that rarely attains 0.5 µm in depth. In comparison, LAM-ICPMS analyses are usually done

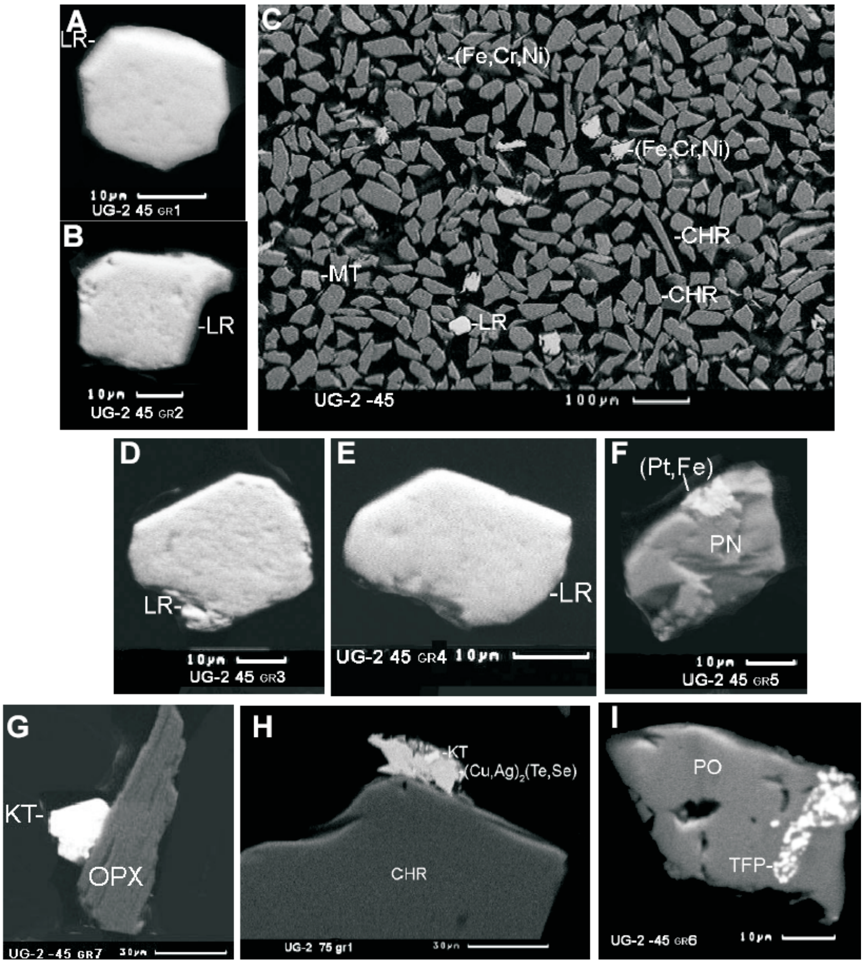

FIG 8 - SEM images showing free laurite particles (A, B, D, E), low magnification view of chromite- and anthropogenic metal-rich concentrate (C), Pt-Fe alloys as a single inclusion in pentlandite (F) and numerous inclusions in pyrrhotite (I); sobolevskite (labelled KT) attached to orthopyroxene (G) and kotulskite included in unknown Cu-Ag-selenide (H).

with 40 µm, 30 µm or 20 µm diameter areas that ablate at a rate of ~1 µm/s at 10 Hz over 60 s. The larger analysis volume of LAM-ICPMS gives a better average. This is especially important on account of precious metal heterogeneity in sulfide minerals and the larger number of analyses that can be done per day, resulting in lower costs/analysis. The remaining advantage of SIMS over LAM-ICPMS is the capability of being able to obtain elemental maps, though this is somewhat mitigated by LAM-ICPMS trace analyses in raster mode across grain surfaces.

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