Platinum-Group Elements in Magnetic Concentrates from the Goodnews Bay District, Alaska

By SAM ROSENBLUM, R. R. CARLSON, J. M. NISHI, and W. C. OVERSTREET

Platinum-group elements (PGE) occur in magnetic concentrates as discrete mineral grains, as inclusions in magnetite, and as diffused atoms in the magnetite lattice. The finer fractions of the magnetic concentrates contain the greatest amounts of PGE

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CONTENTS

FIGURES

TABLES

Platinum-Group Elements in Magnetic Concentrates from the Goodnews Bay District, Alaska

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Abstract

Platinum-group elements (PGE) occur in ferromagnetic concentrates from placer deposits in the Goodnews Bay district, Alaska, and analyses showed platinum values are as high as 1,100 parts per million (ppm) (35.37 troy ounces per ton). Scanning electron microscope studies showed at least seven mineral phases that contain the following associations of PGE: platinum-iron (Pt-Fe) alloy, sperrylite (Pt-As), unknown A (Ir-Fe alloy), unknown B (Ir-Rh-Pt-Fe-As-S), hollingworthite (Rh-As-S), unknown C (Rh-Pd-Ni-As-S), and unknown D (Pb-Rh-Fe-Ir-S). In each association, variable amounts of PGE and minor elements (chromium, copper, nickel), as determined by the semiquantitative X-ray dispersive method, made the assignment of definite compositions difficult.

PGE minerals occur as discrete grains in the magnetic concentrate and as inclusions in magnetite. Furthermore, PGE apparently have diffused into magnetite adjacent to the borders of PGE minerals. Such PGE may be held in the magnetite lattice and represent a valuable resource lost during extractive metallurgy, but this possibility needs to be tested.

Grain sizes of the various equant PGE-bearing inclusions in three magnetite grains ranged from less than 1 μm to about 80 μm. These minerals generally formed irregular inclusions in magnetite hosts that were 0.2–0.4 mm across. Discrete amoeboid grains of Pt-Fe alloy in two fine-grained concentrates were 25 by 55 to 40 by 80 μm in size. The average grain size for equant Pt-Fe-alloy inclusions was about 12 μm, and the average for bladed Ir-Fe alloy inclusions was about 1 by 12 μm.

Fire-assay and emission spectrographic analyses of 12 of 14 sized groups of magnetic concentrates showed that the finest grained fractions contained the greatest amounts of PGE, but the increase in amount was not always in direct relation to decreasing grain size. Five of the fourteen sets indicated a second, less abundant population of PGE in the coarse-grained fractions.

We recommend expansion of the study of PGE in magnetite to include magnetite from mafic and ultramafic rocks from other parts of Alaska as well as geologically suitable areas in the conterminous United States. A study is needed to find methods for improving sample preparation and analytical techniques to enable more rapid acquisition and reliability of results of analyses for PGE in magnetite. Also, as the semiquantitative fire-assay and emission spectrographic analyses showed the presence of gold in the magnetite, a study is needed to determine the mode of occurrence of the gold.

INTRODUCTION

Background

The use of detrital magnetite as a geochemical sample medium has been under investigation in the United States Geological Survey and in the Canadian Department of Energy, Mines, and Resources since the early 1960's (Theobald and others, 1967; Nakagawa, 1975; Raicevic and Cabri, 1976; Thayer and others, 1977; Overstreet and others, 1978; Pan and others, 1980). The discovery by Erickson and others (1966), through geochemical means, of economic deposits of disseminated micrometer-sized gold at Cortez, Nev., led Overstreet to postulate that fine-grained platinum metals, in particles too small to accumulate in placers and thus not amenable to identification by panning, might be present in source rocks as discrete grains and as inclusions in magnetite. Such grains of magnetite could easily be recovered from alluvial sediments by panning or other methods of concentration for recovery of the PGE (platinum group elements) contained therein.

The conceptual basis of genesis was that in an appropriate cooling magma, myriads of centers of nucleation

for the platinum-group metals could occur without extensive migration of the metals. The result would be large numbers of small grains with compositions crystallized from the Pt-Pd-Fe-As-S system, as summarized by Skinner and others (1976). Some of these grains, even ones only a few micrometers across, could serve as centers for the later overgrowth of magnetite; and the magnetite could be expected to attain sizes commonly associated with accessory minerals in igneous rocks. Platinum-bearing magnetite would readily accumulate in alluvial deposits with other heavy minerals. Even in rocks where the platinum failed to form grains large enough to be retained in placers during the erosion of the source rock, its presence could be detected by analysis of detrital magnetite. Thus, source rocks presently not known to contain platinum might be discovered through the study of detrital magnetite as a preferred geochemical sample medium.

This concept was promoted by John B. Mertie, Jr., former platinum-commodity geologist for the U.S. Geological Survey, who noted that the black sand concentrates from the platinum placers in the Goodnews Bay district, Alaska, were commonly crushed to improve the recovery of the platinum metals. Because of his interest, and through the cooperation of the Goodnews Bay Mining Company, Mertie sent to the writers two suites of magnetic concentrates from the Goodnews Bay district (fig. 1). These magnetic concentrates provided the sample material on which this present laboratory investigation is based.

Purpose of Present Study

The association of PGE with the spinel, chromite, is well known in the Goodnews Bay district (Mertie, 1969, p. 87) as well as in other areas of ultramafic rocks such as the Stillwater Complex, Mont. (Grimaldi and Schnepfe, 1969; Page and others, 1969; Page and Carlson, 1980), in the Tulameen River area of British Columbia, Canada (Cabri, 1974; Raicevic and Cabri, 1976), and in South Africa at several PGE deposits (Gijbels and others, 1974; Vermaak and Hendriks, 1976; Cabri and others, 1977; Crockett, 1979). The association of PGE with the spinel, magnetite, has been noted by Page and others (1973, p. 543), Snetsinger (1973), Fominykh and Znamenskiy (1975), Volchenko and others (1975), Begizov and others (1975), Chyi and Crocket (1976), and Raicevic and Cabri (1976). Because PGE are in or attached to magnetite, the Goodnews Bay Mining Company crushed and concentrated all the magnetite concentrates during the last years of operation in order to recover the contained PGE (Mertie, 1976, p. 12). Platinum values in magnetite reported in the literature include the following: 0.12–0.47 parts per million (ppm) in the Tulameen River area (Raicevic and Cabri, 1976), 244–858 parts per billion (ppb) in the Sudbury, Ontario, district of Canada (Chyi and Crocket, 1976), and

0.01–0.42 ppm in the Ural platinum belt (Fominykh and Znamenskiy, 1975; Volchenko and others, 1975). These magnetites were all associated with mafic or ultramafic rocks, but platinum values from 0.016 to 0.08 ppm were also reported for magnetites from calcalkaline rocks ranging in composition from diorite to granite (Fominykh and Znamenskiy, 1975).

In the present study, samples of magnetic concentrates from the Goodnews Bay district were examined to characterize the modes of occurrence of PGE in these concentrates, particularly in magnetite, and to utilize magnetic concentrates as geochemical sample media for PGE. To our knowledge, no similar study using chromite concentrates has been done. On the basis of the identification of mineral hosts and actual sites of PGE, we anticipated making recommendations for (1) recovery of PGE, (2) further investigations to characterize PGE occurrences in worldwide magnetic concentrates from mafic and ultramafic terranes, and (3) the use of magnetic concentrates as a geochemical sample medium for PGE.

ACKNOWLEDGMENTS

METHODS OF STUDY AND RESULTS

Two suites of magnetic concentrates from the Goodnews Bay district, Alaska, were received from J. B. Mertie, Jr., during 1972–73. They bore his field numbers, and they were designated in our study as the preliminary set of magnetic concentrates (21 fractions) and the later set of magnetic concentrates (89 fractions). The reader is referred to Mertie (1976, figs. 2, 3, and p. 35–37) for geologic and claim maps and sample locations.

The preliminary set consisted of four groups of magnetic concentrates prepared from two commercial

Figure 1. Index map of part of southwestern Alaska showing location of Goodnews Bay district (modified from Mertie, 1976, fig. 1).

dredge concentrates from the Salmon River and one concentrate panned from beach sand on the shore of the Pacific Ocean south of Red Mountain (Mertie, 1976, fig. 2). These magnetic concentrates had been sieved by hand by Mertie to as many as six sizes (making a total of 21 fractions) before transmittal to us for study.

The later set consisted of 20 concentrates from dredge cleanups, exploration drill-hole samples, and panned alluvium from the Salmon River drainage as well as panned concentrates from the Pacific Ocean beach. These samples had not been sieved or separated into magnetic and nonmagnetic fractions. We selected 14 of these concentrates, and using Tyler screens with mesh numbers 12 (1.410 mm), 24 (0.70 mm), 42 (0.354 mm), 80 (0.177 mm), and 170 (0.088 mm), we divided each concentrate into groups of 6 sieve fractions of decreasing grain size. The sixth fraction was less than 170 mesh (–0.088 mm). Again, not all the samples yielded six fractions. To these were added several nonmagnetic fractions to make the 89 fractions sent for analysis.

Because the sized fractions of the preliminary set were large, the 21 sieved fractions of magnetic concentrates were used to perfect the fire-assay and emission spectrographic method that was used to analyze for PGE and gold. Many replicate analyses and variations in technique were made on them to determine if PGE were actually present in the magnetic concentrates. When the pres-

ence of the PGE was confirmed and the analytical technique was considered satisfactory, the later set of 20 concentrates was studied using the following procedures:

1. Magnetic separation with hand magnet;
2. Splitting of magnetic fractions into two parts, one for analyses and the other for making polished sections;
3. Sieving of split for analysis into six size fractions using a Ro-Tap machine[1] to shake the concentrates for 10 minutes;
4. Semiquantitative fire-assay and emission spectrographic analyses of one split of the sized concentrates for PGE and gold;
5. Semiquantitative emission spectrographic analyses of another split of each of the sized concentrates for 30 elements;
6. Metallographic microscope analyses of polished sections of all magnetic concentrates to locate grains with PGE-bearing minerals. Only five grains with PGE minerals were recognized;
7. Scanning electron microscope (SEM) analyses of selected inclusions in the magnetic grains done with an attached energy-dispersive spectrometer.

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[1]The use of trade names is for descriptive purposes only and does not constitute endorsement of this product by the U.S. Geological Survey.

Preliminary scan by electron microprobe was made on some inclusions.

Semiquantitative Fire-assay and Emission Spectrographic Analyses

Experimentation on the 21 preliminary magnetic fractions using the semiquantitative fire-assay and emission spectrographic analytical technique of Cooley and others (1976) for platinum, palladium, rhodium, ruthenium, iridium, and gold produced an optimum PGE recovery with a fire-assay flux of 80 g PbO, 15 g SiO_2, 30 g Na_2CO_3, 15 g $Na_2B_4O_7$, and 1.8 g graphite for approximately 3 g of each sample. Four to eight milligrams of gold wire were added to the flux to collect the PGE in the cupellation step. Therefore, gold was not determined by the fire-assay analyses in these initial samples. Three replicate analyses on each of the 21 preliminary fractions produced platinum values with relative standard deviations that ranged from 16 percent to 70 percent for each fraction.

The precision and accuracy of the analyses were increased by investigating sampling errors due to small sample size and losses of PGE to the fire-assay fusion slag. Because samples larger than about 3 g tended to overload the digestive capacity of the flux, sampling errors due to small sample size were reduced by combining the results of replicate analyses. Losses of PGE to the slag during fusion were studied from both mechanical and chemical points of view. Microscopic examination of the slags found no undigested magnetite grains, even where the sample grain size was as great as 1.65 mm; thus, mechanical losses were ruled out. However, fine grinding of the magnetite before fusion produced dramatic increases in recovered PGE, perhaps indicating some "chemical losses" during fusion of coarser grains of magnetite. Here, "chemical losses" refers to any number of complex chemical conditions or reactions in the fusion process that result in either a nonreduction of PGE to the metallic state or transformation of complexes of PGE to an overall oxidized state. Each of these conditions can cause subsequent loss of these elements to the silicate slag. Fine grinding of the samples possibly allowed for early exposure of PGE to reducing conditions that were absent later in the fusion process.

Because grinding of a sample containing noble metals can produce significant losses of these metals to the grinding apparatus, a test of various grinding methods was applied to four splits of sample number 66AMt7N3 to optimize the PGE recovery. The following table summarizes results of two of these grinding methods. It points out some of the hazards of preparing platinum-bearing magnetites for analysis.

Split	Sample preparation	Average grain size analyzed, in millimeters	Mean recovered Pt value, in parts per million	Precision, in percent[1]
1	None	0.527	31	76
2	Coarse grind with ceramic plates	.279	1.9	100
3	Fine grind with ceramic plates	.059	43	86
4	Fine grind with agate mortar and pestle	.061	130	4

[1]Relative standard deviation, in percent = std. dev. ×100 percent/mean recovered Pt value. Replicate analyses=3.

The loss of platinum-group metals (PGM) to the ceramic grinding plates can be seen in comparing recovered platinum in the coarse-ground split to that in the unground split. A twenty-three-fold increase in platinum recovery can be seen in comparing the ceramic-plate fine grind to the coarse grind. The additional threefold increase in platinum recovery, and twentyfold increase in precision, of the fine grind on agate versus the fine grind on ceramic plates indicates that a fine grind or milling of these samples, using relatively nonporous and hard materials, would optimize PGE recovery. Re-fusion of fire-assay slags from the unground and coarse-ground splits recovered no significant amounts of PGE; possibly the PGE are too strongly bound chemically to the silicate phase to be reduced by the standard lead-based assay.

Further experimentation with sample preparation led to the use of a Bleuler eccentric mill equipped with a 50-g grinding pot; PGE recovery from samples so ground was similar to recovery from agate-ground samples. Sample preparation by Bleuler milling was chosen over hand-grinding in an agate mortar as a means of reducing human bias in preparation and because hand-grinding coarse-grained samples causes sample loss through ejection of grains.

The use of these new methods of sample preparation and the flux described earlier to accommodate the magnetite host allowed a threefold increase in sensitivity (detection limit) and a far greater increase in precision relative standard deviation (RSD) over older methods. The results of fire-assay and emission-spectrographic analysis are given in table 1. The lower limits of determination (one to two spectrographic report intervals above the lower limits of detection (Cooley and others, 1976)) for the PGE in parts per billion are as follows: Ru, 100–200; Rh, 1–2; Pd, 1; Ir, 50–100; and Pt, 2–5. Osmium is volatilized during the fire assay and is not reported. Of the four sam-

ples that showed greater than 50 ppm platinum, two were estimated at about 80 and 700 ppm.

Semiquantitative spectrochemical analyses for 30 elements other than the PGE were also made on the 21 preliminary fractions. The results showing the most pertinent data are given in table 2. Not shown in table 2 are data for Fe, which is 50 percent or greater for all samples; Ba, with only 8 samples containing as much as 50 ppm— the limit of detection; Pb, with 10 samples containing 20 ppm and 1 containing 100 ppm; Zn, with 1 sample containing 500 ppm and 3 others, 1,000 ppm; and Zr, with 9 samples containing 20 ppm and 3 containing 30 ppm. Looked for but not found were Ag, As, Au, B, Bi, Cd, La, Mo, Nb, Sn, Sr, W, and Y.

The data in table 2 resemble trace-element compositions previously reported for magnetic concentrates from ultrabasic areas elsewhere in Alaska (Overstreet and others, 1978) except for greater amounts of chromium. The probable significance of these minor elements is discussed near the end of this section.

The later set of 89 magnetite fractions was analyzed using 9.3 mg silver as a fire-assay collector so that gold could be determined along with the PGE. The results of the semiquantitative fire-assay and emission spectrographic analyses for PGE and gold on the 89 fractions are given in table 3, and the results of the semiquantitative spectrographic analyses for the non-PGE elements in the same samples are listed in table 4.

As many as seven replicate analyses were made by fire-assay and emission spectrography on each size fraction in table 3, and the results are reported there as mean values. The weight shown for each sample in table 3 is the sum of the sample weights used in these replicate analyses. An approximate 3 g sample weight was chosen as an amount of magnetite that would not exceed the fusion and collection capabilities of the flux.

The later set of 89 size fractions was prepared using a 15-g silica cleanup of the mill pot after each fraction. The cleanup silica from the mill pot was used as the 15-g silica flux component for one of the 3-g samples of that fraction. The lower platinum value reported for sample 66AMt7N3 in table 3, compared to recovered platinum in earlier experimentation, probably reflected the uneven distribution (particulate nature) of PGE within any one screened fraction of magnetite. However, the magnitude of this variance was not sufficient to negate the trends of PGE distribution seen within each of the 14 groups of 6 screened fractions (table 3).

Of the 14 sets of size-graded samples listed in table 3, 12 showed a general, but erratic, increase in platinum values with decreasing grain size. In samples 69AMt6A and 69AMt14A, the greatest platinum values were in the second and third sieve fractions; the sixth fraction in each was not high. Paladium, rhodium, ruthenium, and iridium values were erratic; but where the platinum values were

high, generally one or more of these PGE was correspondingly high.

Despite these specific observed inconsistencies for direct increase in concentrations of the PGE with decreasing grain size, the finest particles of detrital magnetite strongly tended to contain the most PGE. When the values for the PGE determined for the coarsest sieve sizes and the finest sieve sizes were compared in samples where one or both of the pair of sieve fractions contained detectable PGE, the finest size magnetic fraction virtually always contained more PGE than the coarsest sieve fraction. The following table confirms this observation.

Element	Number of sieve pairs showing element	Number of sieve pairs in which the greatest concentration of PGE was in the finest fraction
Pt	14	14
Pd	13	11
Rh	11	11
Ru	1	1
Ir	7	7

These relations show that the finest sieve fraction of the magnetic concentrate at the Goodnews Bay Mining district is the preferred host for PGE in the magnetic concentrate. By sieving to fine size, an initial enrichment in PGE could be made so that the amount of PGE in the analysis was increased over that of the whole unsized sample, and the results of analyses offered greater contrasts for comparisons than those of the whole samples.

Gold (table 3) followed essentially the same pattern as the PGE in relation to the size of the host grains of detrital magnetite. Except for the set represented by sample 69AMt5, where all sieve fractions were auriferous and were rich in PGE, the gold tended to be most abundant in sieve sizes smaller than 0.177 mm. No correlation existed between the amounts of gold and of such elements as copper, nickel, and zinc which suggested that the gold was not present in inclusions of sulfide minerals in the detrital magnetite. Evidently native gold was present in the detrital magnetite, perhaps alloyed with the PGE, but this subject was not pursued in this investigation. In another study (Overstreet and others, 1978) gold was indeed found in magnetite.

Comparison of 14 analyses that showed platinum values of 90 ppm or more (table 3) with analyses for PGE in samples free of black sand, presented by Mertie (1976, p. 16), showed qualitatively similar results. In both sets, platinum was by far the most abundant element; iridium was next, followed by rhodium, palladium, and ruthenium. When our PGE values and the values for the principal alloy, shown in Mertie's tables 5, 7 and 13

Table 1. Results of semiquantitative fire-assay and emission spectrographic analyses of platinum-group elements in 21 preliminary magnetic concentrates from the Goodnews Bay district, Alaska

[Analysts: R. R. Carlson and E. F. Cooley. G, greater than value shown in parentheses; N, not detected at lower limit of detection shown in parentheses]

Sample No.[1]	Size, in millimeters	Weight, in grams	Parts per million				
			Pt	Pd	Rh	Ru	Ir
66AMt7A1	>25	3.0	1	0.15	N(0.01)	N(0.50)	N(0.25)
66AMt7A2	25 - 20	3.0	1	.01	N(.01)	N(.50)	N(.25)
66AMt7A3	20 - 15	3.0	.3	.03	N(.01)	N(.50)	N(.25)
66AMt7A4	15 - 10	3.0	.1	.015	N(.01)	N(.50)	N(.25)
66AMt7B	10 - 3.33	3.0	.1	.05	N(.01)	N(.50)	N(.25)
66AMt7C	3.33 - 2.36	3.0	1	.05	N(.01)	N(.50)	N(.25)
66AMt7D	2.36 - 1.65	3.0	.2	.02	N(.01)	N(.50)	N(.25)
66AMt7E	1.65 - 1.17	3.0	20	.30	.20	N(.50)	1
66AMt7F	1.17 - .83	3.0	30	.15	.30	N(.50)	2
66AMt7G	.83 - .59	3.0	30	.20	.50	N(.50)	7
66AMt7H	.59 - .42	3.0	20	.15	.70	N(.50)	7
66AMt7I	.42 - .29	3.0	50	.30	.50	N(.50)	2
66AMt7J	.29 - .21	3.0	G(50)	.30	.70	.50	5
66AMt7K	.21 - .15	3.0	G(50)	.30	1	.50	5
66AMt7L	.15 - .10	3.0	G(50)	.50	1.5	N(.50)	3
66AMt7M	<.10	3.0	G(50)	3	7	.70	15
69AMt9A	<.29	7.5	.3	.03	.015	N(.20)	N(.10)
69AMt9B	.29 - .21	7.5	.2	.03	.015	N(.20)	N(.10)
69AMt9C	.21 - .15	7.5	.1	.02	.007	N(.20)	N(.10)
69AMt9D	<.15	.5	1.5	N(.06)	N(.06)	N(3)	N(1.5)
72AMt1	Unsized	7.5	7	.10	.07	N(.2)	.30

[1]Localities of magnetic concentrates (from Mertie, 1976, fig. 3, plot of Salmon River drainage and claims):

> 66AMt7 series—Dredge concentrates from valley floor, Salmon River, claim 12 below Discovery claim.
> 69AMt9 series—Pacific beach, a short distance south of the ultrabasic promontory of Red Mountain.
> 72AMt1—Dredge concentrate from Fourth of July bench claim, Salmon River.

Table 2. Results of semiquantitative spectrographic analyses of elements other than platinum-group elements in 21 preliminary magnetic concentrates from the Goodnews Bay district, Alaska

[Analysts: D. F. Siems and W. D. Crim. G, greater than value shown in parentheses; L, less than the value shown in parentheses]

Sample No.[1]	Size, in millimeters	Percent			Parts per million						
		Mg	Ca	Ti	Mn	Co	Cr	Cu	Ni	Sc	V
66AMt7A1	>25	3	1.5	2	3,000	200	500	15	300	50	3,000
66AMt7A2	25 - 20	3	.3	G(2)	3,000	300	700	20	500	30	5,000
66AMt7A3	20 - 15	2	.3	G(2)	3,000	200	700	15	500	20	5,000
66AMt7A4	15 - 10	2	.5	2	3,000	300	1,000	15	500	20	5,000
66AMt7B	10 - 3.33	2	.5	2	3,000	300	1,500	10	500	20	5,000
66AMt7C	3.33 - 2.36	2	.2	G(2)	5,000	300	2,000	20	500	20	5,000
66AMt7D	2.36 - 1.65	2	.2	2	5,000	200	2,000	15	500	20	5,000
66AMt7E	1.65 - 1.17	1.5	.3	2	3,000	300	3,000	15	500	20	5,000
66AMt7F	1.17 - 0.83	1.5	.2	2	3,000	300	5,000	10	500	20	5,000
66AMt7G	.83 - 0.59	1.5	.3	2	3,000	150	10,000	10	500	20	5,000
66AMt7H	.59 - 0.42	1	.2	1	2,000	150	G(10,000)	10	500	15	3,000
66AMt7I	.42 - 0.29	1.5	.15	1.5	3,000	150	G(10,000)	10	700	15	5,000
66AMt7J	.29 - 0.21	1.5	.2	1	3,000	150	G(10,000)	15	700	10	3,000
66AMt7K	.21 - 0.15	1.5	.15	1	3,000	150	G(10,000)	15	700	15	3,000
66AMt7L	.15 - 0.10	1.5	.15	1	5,000	150	G(10,000)	15	1,000	20	3,000
66AMt7M	<.10	1	.15	1	3,000	200	G(10,000)	50	700	15	3,000
69AMt9A	>0.29	1.5	.15	1.5	5,000	200	G(10,000)	L(10)	1,000	20	3,000
69AMt9B	.29 - 0.21	1.5	.1	1	3,000	150	G(10,000)	L(10)	1,000	20	2,000
69AMt9C	.21 - 0.15	1.5	.1	1	5,000	200	G(10,000)	L(10)	1,000	20	3,000
69AMt9D	<.15	1.5	.2	1	3,000	200	G(10,000)	150	700	20	3,000
72AMt1	Unsized	1.5	.1	1.5	3,000	150	G(10,000)	L(10)	700	20	3,000

[1]Localities of magnetic concentrates (from Mertie, 1976, fig. 3, plot of Salmon River drainage and claims):

66AMt7 series—Dredge concentrates from valley floor, Salmon River, claim 12 below Discovery claim.

69AMt9 series—Pacific beach, a short distance south of the ultrabasic promontory of Red Mountain.

72AMt1—Dredge concentrate from Fourth of July bench claim, Salmon River.

Table 3. Results of semiquantitative fire-assay and emission spectrographic analyses of platinum-group elements and gold in 89 magnetic concentrates from the Goodnews Bay district, Alaska, including six nonmagnetic concentrates for comparison

[Analysts: R. R. Carlson and E. F. Cooley. Sample numbers for the nonmagnetic concentrates are 69AMt9F, 72AMt1L, 72AMt1M, 72AMt1P, 72AMt1Q, and 72AMt2G; all nonmagnetic concentrates are unsized; N, not detected at lower limit of detection shown in parentheses]

Sample No.[1,2]	Weight, in grams	Parts per million					
		Pt	Pd	Rh	Ru	Ir	Au
66AMt7N1	9.076	0.07	0.025	0.007	N(0.35)	0.60	0.012
66AMt7N2	10.703	.45	.020	.008	N(.40)	.40	.30
66AMt7N3	10.303	50	.12	.20	N(.45)	1.1	.1
66AMt7N4	10.811	160	.60	.60	N(.40)	2.0	.2
66AMt7N5	7.622	180	.40	.30	N(.60)	3.0	.4
66AMt7N6	.908	1,100	2.0	3.5	N(1.7)	35	7.0
66AMt9A1	.222	.45	.10	N(.07)	N(7)	N(7)	N(.07)
66AMt9A2	1.380	.40	.035	.02	N(1.0)	N(1.0)	.020
66AMt9A3	11.488	.60	.017	.012	N(.13)	N(.13)	.010
66AMt9A4	12.231	.30	.017	.007	N(.12)	N(.12)	.012
66AMt9A5	2.423	.30	.012	.012	N(.60)	N(.60)	.012
66AMt9A6	.298	14.0	.350	.08	N(5.0)	N(5.0)	3.5
66AMt30A1	12.303	.10	.020	N(.004)	N(.18)	N(.035)	.040
66AMt30A2	4.832	.14	.020	N(.009)	N(.45)	N(.09)	.035
66AMt30A3	11.988	.15	.008	N(.004)	N(.19)	N(.04)	N(.009)
66AMt30A4	14.876	.14	.002	N(.003)	N(.15)	N(.03)	N(.007)
66AMt30A5	9.836	2.0	.011	.02	N(.25)	N(.045)	N(.011)
66AMt30A6	.150	8.0	N(.10)	N(.30)	N(15)	N(3.0)	.70
66AMt31A1	8.766	.035	.003	N(.005)	N(.25)	N(.05)	N(.012)
66AMt31A2	1.019	N(.045)	N(.015)	N(.045)	N(2.0)	N(.45)	N(.10)
66AMt31A3	7.842	35	.03	.20	N(.30)	2.0	.040
66AMt31A4	17.229	10	.04	.20	N(.13)	.50	.045
66AMt31A5	16.388	50	.12	.60	N(.14)	1.6	.50
66AMt31A6	1.101	200	.70	2.5	N(2.0)	6	N(.10)
66AMt32A1	.319	N(.14)	N(.045)	N(.14)	N(7)	N(1.4)	N(.35)
66AMt32N2	1.062	N(.04)	N(.014)	N(.04)	N(2.0)	N(.40)	N(.10)
66AMt32A3	6.828	17	.04	.25	N(.35)	.45	N(.015)
66AMt32A4	11.361	14	.013	.04	N(.20)	1.7	.080
66AMt32N5	3.748	14	.35	.06	N(.60)	N(.12)	.25
66AMt32A6	.053	30	N(.30)	N(.80)	N(40)	N(8)	N(2.0)

Table 3. Continued

Sample No.[1,2]	Weight, in grams	Parts per million					
		Pt	Pd	Rh	Ru	Ir	Au
66AMt35A1	4.350	.10	.01	N(.01)	N(.50)	N(.10)	N(.025)
66AMt35A2	4.776	.30	.03	N(.009)	N(.45)	N(.09)	N(.020)
66AMt35A3	17.473	.035	.01	N(.003)	N(.13)	N(.025)	N(.006)
66AMt35A4	16.078	.02	.008	N(.003)	N(.14)	N(.03)	N(.007)
66AMt35A5	9.441	.035	.016	.005	N(.2)	N(.05)	N(.011)
66AMt35A6	.828	10	.07	.13	N(2.5)	N(.50)	N(.13)
68AMt4A1	2.200	.30	.035	N(.02)	N(1.0)	N(.20)	N(.050)
68AMt4A2	5.687	.12	.005	N(.008)	N(.40)	N(.08)	.035
68AMt4A3	6.877	.12	.004	N(.007)	N(.35)	N(.06)	N(.015)
68AMt4A4	11.611	.20	.003	N(.004)	N(.19)	N(.04)	.060
68AMt4A5	14.588	.30	.02	N(.003)	N(.15)	N(.03)	.080
68AMt4A6	1.932	110	.60	1.6	1.6	19	12
69AMt5A1	11.932	8	.045	.16	N(.19)	.45	.25
69AMt5A2	10.152	.30	.019	N(.004)	N(.20)	N(.045)	3.0
69AMt5A3	11.429	40	.25	.70	.25	2.5	40
69AMt5A4	13.671	90	2.0	.70	N(.16)	3.0	60
69AMt5A5	15.299	120	1.3	2.0	N(.15)	12	40
69AMt5A6	1.407	180	3.0	1.2	N(1.6)	20	80
69AMt6A1	9.736	.03	.003	.005	N(.30)	N(.15)	.006
69AMt6A2	5.356	200	.70	2.0	N(.60)	4.5	.020
69AMt6A3	17.911	100	.19	1.0	N(.13)	1.7	.080
69AMt6A4	14.507	.40	.008	.006	N(.15)	N(.03)	N(.007)
69AMt6A5	14.767	1.1	.017	.01	N(.15)	N(.03)	N(.007)
69AMt6A6	13.212	15	.05	.35	N(.17)	2.0	.70
69AMt9E2	5.427	1.5	.017	.04	N(.40)	N(.08)	.050
69AMt9E3	11.600	.08	.013	.01	N(.19)	N(.04)	N(.009)
69AMt9E4	11.507	.08	.015	N(.001)	N(.25)	N(.13)	N(.001)
69AMt9E5	9.161	6	.08	.005	N(.35)	N(.16)	N(.002)
69AMt9E6	.064	180	.90	2.5	N(45)	N(25)	N(.25)

Table 3. Continued

Sample No.[1,2]	Weight, in grams	Parts per million					
		Pt	Pd	Rh	Ru	Ir	Au
69AMt9F	14.070	1.9	.003	.012	N(.20)	N(.11)	4.0
69AMt14A1	14.390	.06	.009	N(.001)	N(.20)	N(.10)	L(.001)
69AMt14A2	15.569	400	.19	.05	.60	30	.10
69AMt14A3	14.837	.40	.015	N(.001)	N(.25)	N(.13)	.004
69AMt14A4	11.227	45	.25	.045	N(.25)	10	.60
69AMt14A5	18.750	3.0	.04	N(.001)	N(.19)	.15	.80
69AMt14A6	15.588	2.5	.06	N(.001)	N(.19)	.60	.045
69AMt15A1	.312	N(.25)	N(.05)	N(.05)	N(10)	N(5.0)	N(.050)
69AMt15A2	4.335	3.0	.02	.025	N(.70)	N(.35)	.003
69AMt15A3	18.222	.11	.011	.006	N(.16)	N(.08)	.001
69AMt15A4	11.161	.13	.011	.001	N(.25)	N(.13)	N(.001)
69AMt15A5	10.823	.30	.017	.003	N(.30)	N(.14)	.006
69AMt15A6	.116	110	1.3	1.6	N(25)	N(13)	1.2
69AMt18A1	.602	N(.12)	.012	N(.025)	N(5.0)	N(2.5)	N(.025)
69AMt18A2	4.166	.30	.004	N(.004)	N(.70)	N(.35)	.007
69AMt18A3	13.483	.25	.01	.03	N(.20)	N(.11)	.011
69AMt18A4	17.991	4.5	.016	.05	N(.17)	.35	.025
69AMt18A5	13.238	1.3	.025	.008	N(.25)	N(.11)	.060
69AMt18A6	13.060	8	.06	.06	N(.30)	N(.14)	.11
72AMt1L	7.357	.07	.002	N(.002)	N(.40)	.25	.030
72AMt1M	16.717	130	.50	1.4	.35	1.7	3.0
72AMt1N1	11.382	.05	.012	N(.001)	N(.25)	N(.13)	.002
72AMt1N2	16.368	.40	.016	N(.001)	N(.18)	N(.09)	.003
72AMt1N3	15.483	.50	.017	.004	N(.19)	N(.10)	.002
72AMt1N4	17.043	3.0	.013	.004	N(.18)	N(.09)	.007
72AMt1N5	13.063	.80	.005	.005	N(.25)	N(.12)	.013
72AMt1N6	6.588	16	.16	.40	N(.45)	2.5	.20

Table 3. Continued

Sample No.[1],[2]	Weight, in grams	Parts per million					
		Pt	Pd	Rh	Ru	Ir	Au
72AMt1P	7.377	1.2	.02	.01	N(.40)	N(.20)	.004
72AMt1Q	9.950	17	.14	.14	N(.30)	6	2.5
72AMt2G	12.104	13	.08	.12	N(.25)	3.0	.40

[1]Localities of samples (from Mertie, 1976, fig. 3, plot of Salmon River drainage and claims):

66AMt7 series—Dredge concentrates from valley floor, Salmon River, claim 12 below Discovery claim.

66AMt9 series—Overburden, 20 ft (6.1 m) below ground surface, bench paystreak opposite claim 8 above Discovery claim, Salmon River.

66AMt30 series—Bed of Clara Creek about 100 ft (30 m) upstream from the crossing of the road to Platinum.

66AMt31 series—Cleanup of "Mudhog" operation, bench paystreak, east of claim 4 below Discovery claim, Salmon River.

66AMt32 series—Bed of McCann Creek about 100 ft (30 m) upstream from the crossing of the road to Platinum.

66AMt35 series—Bed of Smalls River about 0.25 mi (0.4 km) from the mouth of McCann Creek.

68AMt4 series—Deep drill hole on Hannah bench claim, valley of the Salmon River; sample is a composite of entire section cut by drill hole.

69AMt5 series—Dredge concentrate from valley floor, claim 11 below Discovery claim, Salmon River.

69AMt6 series—Drill hole 140 ft (42.7 m) deep on Alice Association bench claim, valley of Salmon River; sample is a composite of entire drill hole.

69AMt9 series—Pacific beach, a short distance south of the ultrabasic promontory of Red Mountain.

69AMt14 series—Dredge concentrate from valley floor, claim 11 below Discovery claim; samples 69AMt14 and 69AMt5 were taken from different cleanups.

69AMt15 series—Pacific beach about 1 mi (1.6 km) north of the mouth of the Salmon River.

69AMt18 series—Deep drill hole on bench paystreak south of Happy Creek; sample is a composite of entire drill hole.

72AMt1 series—Dredge concentrate from Fourth of July bench claim, Salmon River.

72AMt2G—Nonmagnetic fraction of composite sample from drill hole on Salmon River bench 1.5 mi (2.4 km) downstream from Fourth of July bench claim.

[2]Sizes of sieved fractions of magnetic concentrates are shown by final numeral in each sample number series:

Final numeral	Size (mm)
1	>1.410
2	1.410–.707
3	.707–.354
4	.354–.177
5	.177–.088
6	<.088

Table 4. Results of semiquantitative spectrographic analyses of elements other than platinum-group elements in 89 magnetic concentrates from the Goodnews Bay district, Alaska, including six nonmagnetic concentrates for comparison

[Analyst: J. A. Domenico. G, greater than value shown in parentheses; L, less than the value shown in parentheses; N, not detected at lower limit of detection shown in parentheses, depending on sample weight; sample numbers for the nonmagnetic concentrates are 69AMt9F, 72AMt1L, 72AMt1M, 72AMt1P, 72AMt1Q, and 72AMt2G; all nonmagnetic concentrates are unsized]

Sample No.[1,2]	Percent			Parts per million								
	Mg	Ca	Ti	Mn	Ba	Co	Cr	Cu	Ni	Sc	V	Zn
66AMt7N1	1.5	.2	G(2)	200	70	200	500	100	300	15	3,000	1,500
66AMt7N2	1.5	.2	2	3,000	70	300	2,000	100	300	15	5,000	1,500
66AMt7N3	1	.2	1.5	3,000	70	300	10,000	70	300	10	2,000	1,500
66AMt7N4	2	.2	2	3,000	70	300	G(10,000)	100	500	15	3,000	5,000
66AMt7N5	1.5	1.5	1.5	3,000	100	200	G(10,000)	50	500	10	3,000	2,000
66AMt7N6	1	.1	1	3,000	100	150	G(10,000)	500	300	N(5)	2,000	2,000
66AMt9A3	5	L(.02)	1	5,000	70	500	G(10,000)	50	700	10	3,000	5,000
66AMt9A4	2	.1	2	3,000	100	500	G(10,000)	100	700	20	3,000	3,000
66AMt9A5	1.5	.1	1.5	3,000	100	200	G(10,000)	70	500	15	1,500	5,000
66AMt9A6	.5	.1	.7	3,000	100	200	G(10,000)	70	300	10	1,000	N(200)
66AMt30A1	3	.7	G(2)	3,000	70	300	7,00	300	500	20	3,000	N(200)
66AMt30A2	1.5	.7	G(2)	3,000	70	300	1,500	200	300	20	3,000	N(200)
66AMt30A3	1.5	.3	1.5	3,000	100	300	G(10,000)	10	300	10	2,000	2,000
66AMt30A4	3	L(.02)	2	5,000	100	300	G(10,000)	20	700	15	3,000	3,000
66AMt30A5	2	L(.02)	2	5,000	100	300	G(10,000)	10	1,000	15	5,000	3,000
66AMt30A6	1.5	L(.02)	1	3,000	100	300	G(10,000)	70	500	10	3,000	2,000
66AMt31A1	2	L(.02)	G(2)	3,000	70	200	1,500	150	500	20	5,000	N(200)
66AMt31A2	1.5	L(.02)	G(2)	3,000	100	300	1,000	500	300	15	2,000	1,500
66AMt31A3	1.5	L(.02)	G(2)	3,000	100	300	G(10,000)	70	700	15	5,000	2,000
66AMt31A4	1.5	L(.02)	G(2)	5,000	100	300	G(10,000)	50	1,000	15	5,000	2,000
66AMt31A5	1.5	L(.02)	G(2)	5,000	100	300	G(10,000)	100	1,000	15	5,000	2,000
66AMt31A6	1	L(.02)	2	3,000	70	200	G(10,000)	150	700	10	5,000	1,500
66AMt32A2	2	1	G(2)	3,000	70	200	2,000	200	500	20	7,000	N(200)
66AMt32A3	1.5	L(.02)	1	3,000	N(20)	200	G(10,000)	50	500	10	3,000	N(200)
66AMt32A4	2	.1	.7	5,000	N(20)	500	G(10,000)	20	500	10	3,000	N(200)
66AMt32A5	3	.1	1.5	10,000	N(20)	700	G(10,000)	30	1,500	20	3,000	N(200)
66AMt35A1	1.5	1	2	3,000	N(20)	300	1,500	100	300	30	3,000	N(200)
66AMt35A2	1.5	.5	2	3,000	N(20)	200	2,000	50	300	20	5,000	N(200)
66AMt35A3	1.5	.5	2	3,000	N(20)	200	5,000	50	300	20	5,000	N(200)
66AMt35A4	1.5	.7	G(2)	3,000	N(20)	200	10,000	70	300	30	5,000	N(200)
66AMt35A5	1	.5	1.5	2,000	N(20)	300	5,000	70	300	15	5,000	N(200)
66AMt35A6	.7	.15	.7	2,000	N(20)	150	5,000	70	300	10	3,000	N(200)

Table 4. Continued

Sample No.[1,2]	Percent			Parts per million								
	Mg	Ca	Ti	Mn	Ba	Co	Cr	Cu	Ni	Sc	V	Zn
66AMt4A1	2	L(.05)	1.5	3,000	N(20)	300	500	100	300	30	3,000	N(200)
66AMt4A2	1	N(.05)	2	3,000	N(20)	300	G(10,000)	100	700	15	5,000	N(200)
66AMt4A3	1.5	N(.05)	2	3,000	N(20)	700	G(10,000)	70	700	15	5,000	N(200)
66AMt4A4	1.5	L(.05)	1	3,000	N(20)	200	G(10,000)	70	700	15	3,000	N(200)
66AMt4A5	1.5	.1	1	3,000	N(20)	300	G(10,000)	100	700	15	5,000	N(200)
66AMt4A6	1	.3	.7	3,000	50	150	G(10,000)	700	500	15	3,000	N(200)
66AMt5A1	1	.5	1.5	3,000	150	200	2,000	50	300	15	3,000	N(200)
66AMt5A2	1.5	.2	1.5	3,000	L(20)	300	5,000	30	500	15	3,000	N(200)
66AMt5A3	2	.5	1	3,000	N(20)	300	G(10,000)	70	500	15	3,000	N(200)
66AMt5A4	2	.3	.7	3,000	N(20)	300	G(10,000)	50	700	15	3,000	N(200)
66AMt5A5	1.5	.2	.7	3,000	N(20)	200	G(10,000)	70	500	10	3,000	N(200)
66AMt5A6	1.5	.5	1.5	3,000	N(20)	300	G(10,000)	300	700	15	3,000	N(200)
69AMt6A1	.5	N(.05)	.1	G(10,000)	30	300	G(10,000)	1,500	2,000	N(5)	1,000	N(200)
69AMt6A2	1	.1	.5	G(10,000)	150	150	G(10,000)	1,000	7,000	N(5)	700	N(200)
69AMt6A3	1.5	L(.05)	1	G(10,000)	50	150	G(10,000)	700	3,000	N(5)	1,500	N(200)
69AMt6A4	1.5	.1	1	3,000	50	200	G(10,000)	150	2,000	10	3,000	N(200)
69AMt6A5	1.5	.15	.7	3,000	L(20)	150	G(10,000)	100	1,000	L(5)	3,000	N(200)
69AMt6A6	1	.1	1	3,000	L(20)	300	G(10,000)	200	1,500	L(5)	3,000	N(200)
69AMt9E2	1.5	.1	1.5	3,000	L(20)	200	G(10,000)	70	1,500	10	5,000	N(200)
69AMt9E3	1.5	L(.05)	1	3,000	N(20)	300	G(10,000)	50	1,000	L(5)	3,000	N(200)
69AMt9E4	1.5	L(.05)	1	3,000	N(20)	300	G(10,000)	20	1,000	L(5)	2,000	N(200)
69AMt9E5	1.5	L(.05)	1	3,000	N(20)	300	G(10,000)	30	1,000	L(5)	3,000	N(200)
69AMt9F	3	.15	1	3,000	100	500	G(10,000)	20	1,500	10	2,000	N(200)
69AMt14A1	1.5	L(.05)	1.5	3,000	L(20)	200	2,000	70	700	L(5)	3,000	N(200)
69AMt14A2	1	L(.05)	1.5	2,000	N(20)	200	5,000	70	700	10	3,000	N(200)
69AMt14A3	1.5	.1	1.5	3,000	N(20)	300	G(10,000)	70	1,000	10	3,000	N(200)
69AMt14A4	1.5	.1	1	3,000	N(20)	300	G(10,000)	70	700	10	2,000	N(200)
69AMt14A5	1	L(.05)	.7	3,000	N(20)	200	G(10,000)	50	500	L(5)	2,000	N(200)
69AMt14A6	1.5	L(.05)	.7	3,000	N(20)	300	G(10,000)	150	500	L(5)	3,000	N(200)
69AMt15A2	1	L(.05)	.7	3,000	N(20)	150	G(10,000	100	300	L(5)	2,000	N(200)
69AMt15A3	1.5	L(.05)	1.5	3,000	N(20)	300	G(10,000)	70	700	15	3,000	N(200)
69AMt15A4	2	.1	1.5	3,000	N(20)	300	G(10,000)	100	700	L(5)	3,000	N(200)
69AMt15A5	1.5	.1	1.5	5,000	N(20)	300	G(10,000)	20	700	10	3,000	N(200)
69AMt15A6	1.5	.1	1	3,000	N(20)	300	G(10,000)	30	700	L(5)	3,000	N(200)

Table 4. Continued

Sample No.[1,2]	Percent			Parts per million								
	Mg	Ca	Ti	Mn	Ba	Co	Cr	Cu	Ni	Sc	V	Zn
69AMt18A2	1.5	L(.05)	1.5	7,000	N(20)	300	G(10,000)	300	1,000	10	5,000	N(200)
69AMt18A3	2	N(.05)	1	5,000	N(20)	200	G(10,000)	70	1,000	10	3,000	N(200)
69AMt18A4	2	N(.05)	1	5,000	N(20)	200	G(10,000)	100	1,000	10	3,000	N(200)
69AMt18A5	1.5	N(.05)	.7	3,000	N(20)	150	G(10,000)	70	500	L(5)	2,000	N(200)
69AMt18A6	1	N(.05)	.7	3,000	N(20)	150	G(10,000)	300	300	L(5)	3,000	N(200)
72AMt1L	3	1.5	1.5	10,000	30	300	G(10,000)	150	700	15	2,000	N(200)
72AMt1M	3	1.5	1.5	7,000	30	300	G(10,000)	100	700	20	1,500	N(200)
72AMt1N1	1.5	.2	2	7,000	30	300	2,000	100	300	20	5,000	N(200)
72AMt1N2	1	L(.05)	G(2)	3,000	N(20)	200	5,000	70	300	15	3,000	N(200)
72AMt1N3	1.5	N(.05)	2	3,000	N(20)	200	G(10,000)	70	500	20	3,000	N(200)
72AMt1N4	1.5	N(.05)	2	3,000	N(20)	300	G(10,000)	70	1,000	20	5,000	N(200)
72AMt1N5	2	N(.05)	1.5	5,000	N(20)	300	G(10,000)	100	700	20	5,000	N(200)
72AMt1N6	1	N(.05)	1	2,000	N(20)	150	G(10,000)	100	500	15	2,000	N(200)
72AMt1P	3	.3	1.5	10,000	N(20)	300	G(10,000)	30	700	20	3,000	N(200)
72AMt1Q	3	5	G(2)	10,000	100	300	G(10,000)	200	700	50	2,000	N(200)
72AM2G	2	5	1.5	10,000	N(20)	150	G(10,000)	70	300	50	1,000	N(200)

Footnote on following page.

(1976, p. 18 and 21), were both converted to atomic percentages, they became remarkably close. The principal alloy was designated by the generic name platinum, although it contained small amounts of the five other PGE. These data indicated, therefore, that the principal alloy is the most abundant PGE phase that will be found and identified under a microscope.

As expected, PGE and gold were also present in the nonmagnetic concentrates reported in table 3: samples 69AMt9F, 72AMt1L, 72AMt1M, 72AMt1P, 72AMt1Q, and 72AMt2G. However, as this investigation was concerned with PGE in magnetic concentrates, these occurrences were merely noted; no further work was done with these nonmagnetic samples.

Table 4 shows chromium was 10,000 ppm or more in a large majority of the analyses. Most likely chromite or chromiferous magnetite was in the sample. The lesser amounts of cobalt, nickel, vanadium, and zinc were un-doubtedly included in the magnetite lattice (Frietsch, 1970; Overstreet and others, 1978; Pan and others, 1980). Copper showed no consistent relation to the PGE or gold in table 3 or to the other minor elements in table 4; hence, we presumed that the copper represented random minor inclusions of copper-bearing minerals such as chalcopyrite.

When the grain size was compared to the amounts of the minor elements in the magnetic concentrates (table 4), it was apparent that the chemical variation between the coarsest and the finest sizes of the magnetic concentrates tended to be less than the variation among samples from different localities. For chromium, however, this observation did not apply. Chromium tended to be strongly enriched in the finest sieve fraction of the 14 groups of sized samples; in 9 of the sets, chromium was most abundant in the finest fraction, but in 5 groups, all sieve sizes had reported concentrations of chromium of over 10,000

ppm. For those five groups, the relation of chromium to grain size could not be determined. For many of the trace elements in table 4, the range in abundance between the coarsest and finest sieve fractions of the magnetic concentrates was no more than three reporting units. This is within the range of accepted analytical variance; thus, the differences may have no geochemical significance. For example, the apparent preponderance of high values in the coarse fractions for calcium, magnesium, titanium, manganese, barium, cobalt, scandium, and vanadium mostly represented only one or two reporting intervals of difference and individually could not be regarded as constituting significant geochemical differences. Collectively, they might indicate a tendency for the coarse grains in the concentrates to be a little richer in these elements than the PGE-enriched finest grains. In general, the values reported for manganese, chromium, copper, nickel, and vanadium in these magnetic concentrates fell in the category of anomalously high values found for these elements in other metal-rich areas in Alaska (Overstreet and others, 1978; Pan and others, 1980). Except for the chromium, and possibly for nickel and vanadium, these minor elements cannot be said to be pathfinder elements for the PGE in magnetic fractions of panned concentrates.

In summary, the results of the semiquantitative fire-assay and emission-spectrographic analyses not only showed that the PGE were present in the magnetic concentrates, but also confirmed the unexpected relationship discovered when the preliminary analyses were done: the finer grained material generally contained greater proportions of PGE than the coarser fractions. In order to use this relationship to advantage as an aid in mineral exploration and in the recovery of PGE, with magnetite itself considered a source of PGE, it became necessary to know the actual form of the PGE in the magnetite grains. Did the PGE occur as inclusions in the magnetite? Were they present as submicroscopic discrete grains, attached somehow to the surface of the magnetite grains in each size

fraction? Or were the PGE within the lattice of the magnetite grains? Perhaps the PGE in the magnetic concentrates were simply present as discrete grains, similar to the other heavy minerals, and rather than being comminuted during fluvial transport, the fine grain sizes represented original small particles liberated by weathering and erosion from their host rocks. The greater amounts of PGE in the finest sizes would then merely reflect the greater number of tiny-particled PGE. These questions required other analytical methods, including polished-section studies and SEM investigations, to resolve the matter of the actual location of the PGE.

Polished-section Studies

Eighty-three polished sections of mounted magnetic-concentrate splits were prepared and studied under the optical metallographic microscope. These magnetic splits represented the series samples in table 3 (where enough material was available), and the chemical results were used to guide the search for PGE minerals in the several size fractions of each set. Those sections that showed brightly reflecting grains were set aside for further study under the SEM, which proved to be an invaluable mineralogical tool for this investigation. The optical microscope showed some of the details of the PGE-bearing grains at 50- to 500-times magnification, especially in oil-immersion mounts, but many of the micro-intergrowths present would never have been detected without the use of the SEM. Under the SEM, these grains were magnified as much as 5,500 times showing the micro-intergrowths and other details of grains originally located with the metallographic microscope; the instrument, with the use of an energy-dispersive spectrometer, also enabled the immediate semiquantitative determination of the composition of tiny areas of these grains.

The chemical results shown in tables 1–4 indicate, in general, the types of mineral phases we could expect to find in the magnetic concentrates as viewed under the metallographic microscope. Most abundant in the 83 polished sections examined were the oxide minerals magnetite, ilmenite, a translucent-to-transparent spinel showing low reflectivity, chromite, and hematite. In addition, lesser amounts of pyrite, chalcopyrite, silicate minerals of calcium, aluminum, iron, and magnesium (pyriboles, inferred from morphology and reflectivity), tramp metals (probably iron alloys), and one grain of gold were identified in the concentrates.

Magnetite most often formed rounded amoeboid grains that showed many fractures and incipient octahedral cleavages. Rarely did the borders of magnetite grains show triangular- or diamond-shaped outlines indicating octahedral forms. A number of rounded chromite grains were mantled with magnetite overgrowths. Except for these two modes, magnetite was not recognized in any other occurrences. Magnetite grains contained inclusions of other minerals, such as pyrite, spinel, ilmenite, rutile, and hematite. Alteration to hematite along fractures and cleavages was common.

The possibility that some of the magnetite was secondary, as described by Eakin (1914, p. 28) and noted by Overstreet and others (1978, p. 42), was indicated by the magnetite mantles on chromite grains, a feature that occurred during serpentinization. However, most of the magnetite was of primary origin, as indicated by the following evidence: (1) exsolution lamellae of ilmenite along crystallographic directions in magnetite grains, (2) inclusion of sulfides like pyrite, (3) source rocks that were magmatic in origin, and (4) all associated heavy minerals in the concentrates that were typical of ultrabasic magmatic provenance. Ramdohr (1969, p. 899–906) thoroughly discussed exsolution and magnetite and stated that this feature occurs especially in magmatic magnetites.

We also found that ilmenite occurred as discrete equant- to lath-shaped grains and as exsolved irregular patches, laths, and needles in magnetite, especially along incipient cleavages. Its color ranged from a pale brown similar to magnetite to a slightly darker brown, but ilmenite was easily recognized by its strong birefringence.

Identification of tranparent spinel minerals was tentative and was based on hardness, transparency (low reflectivity), and equant forms. The grains were observed typically as isotropic inclusions in magnetite and were only rarely present in other minerals. These spinels were generally clear of inclusions.

Chromite formed octahedral-to-rounded equant grains that were similar in color and reflectivity to magnetite, but they showed no cleavages or irregular fractures. Resistance to alteration was greater for chromite than for magnetite. Chromite grains rarely showed inclusions of other minerals, but overgrowths of magnetite on chromite grains were noted in 20 percent of the polished sections. The thickness of the mantles was rarely greater than one tenth of the diameter of the whole grain.

Hematite most commonly occurred as an alteration product of magnetite along irregular fractures and incipient cleavages, where the hematite was easily recognized by its white reflective color and distinctive birefringence under the microscope. Some magnetite grains were almost completely replaced by hematite. Thus, it is likely that this secondary hematite is one of the common detrital minerals in some magnetic concentrates.

Tramp metal, where seen in polished sections of the magnetic concentrates, almost always appeared as bright white metal that showed distinctive lattice patterns between crossed polaroid filters. We assumed these were steel fragments from chipped tools.

PGE minerals seen in polished sections were few and scarcely discernible among the common mineral phases mentioned above. Because all of the PGE-bearing aggregates were tiny and included in magnetite, the pin-

point reflectivities of these aggregates were not easily distinguishable, and all five of the PGE-bearing grains found were overlooked during the first scan. The largest of these aggregates, in sample 69AMt14A2 (grain 1), measured only 220 by 370 μm. An adjacent grain (grain 2) was 220 by 340 μm, and the third grain (grain 3) in this section was only 40 by 100 μm. Single grains in samples 66AMt7N6 and 66AMt31A6 were 25 by 55 μm and 50 by 85 μm, respectively. Except in these 3 polished sections, no PGE minerals were recognized in any of the other 80 polished sections under the metallographic microscope.

Under the microscope, details of the tiny PGE-bearing inclusions in magnetite in sample 69AMt14A2 were difficult to distinguish, even at 500 times magnification. In grain 1, amoeboid inclusions appeared to be homogeneous or to range slightly in reflectivity within one inclusion. In grain 2, fine needlelike forms were seen covering most of the grain, and a few amoeboid inclusions were noted, but the fine details of these PGE minerals were beyond the resolution of the metallographic microscope. Grain 3 in this polished section appeared to be homogeneous. Optical and physical properties of the seven distinctive mineral phases that contained PGE were as follows:

Pt-Fe: bright cream-white, soft, isotropic
Pt-As: gray-white, soft, isotropic
Ir-Fe: yellowish-medium gray, soft, anisotropic (spotty and wavy brown extinctions)
Ir-Rh-Pt-Fe-As-S: gray-white, soft, weakly anisotropic
Rh-As-S: gray-white, soft, isotropic
Rh-Pd-Ni-As-S: slightly yellowish-gray-white, soft, weakly anisotropic
Pb-Rh-Fe-Ir-S: cream-gray, soft, strongly anisotropic (brown tints).

In summary, we found the following distribution of PGE mineral phases among three aggregates that contained PGE:

Sample No.	PGE Mineral Phases
66AMt7N6	Pt-Fe alloy, hollingworthite, sperrylite
66AMt31A6	Pt-Fe alloy
69AMt14A2	All seven mineral phases

Scanning Electron Microscope Studies

To try to resolve the details of PGE microminerals, we used a SEM to study seven different PGE minerals; in addition, we had limited use of an electron microprobe for three of these minerals. The SEM used in this investigation was the Cambridge Stereoscan 180 with magnification capability as much as 100,000 times and resolution capability of less than 100 angstroms when using more than 20 kv. The working voltage, used consistently, was 30 kv. Polaroid photographs were made to record the images seen on the 10- by 13-cm SEM screen. Contrasts in gray tones were usually sufficient to distinguish between adjacent mineral phases, and a scale along the bottom of the SEM screen was used for measurement of the particles. An energy-dispersive spectrometer was used for semiquantitative determination of the composition of a mineral phase under investigation.

Semiquantitative information for elements numbered 11 to 92 was obtained from the 13- by 15-cm screen of the Kevex energy-dispersive spectrometer. The screen was divided into 10 parts vertically, and the relative amounts of the several elements in a mineral phase were indicated by the heights of characteristic peaks (fig. 2). A tiny circle of light on the SEM screen could be placed around a spot on a grain to analyze the composition of that spot, and the peaks on the spectrum displayed on the Kevex screen grew vertically, proportional to the amount of each element present.

Platinum-group Element Phases

General comments.—The mineralogy determined under the SEM, like that determined from examination of the polished sections under the metallographic microscope, could be expected to reflect the results of chemical analysis. Our determinations using the SEM and the energy-dispersion X-ray fluorescence system (herein referred to as Kevex) were based on only a few samples of PGE-bearing grains, so that any semiquantitative chemistry determined by Kevex probably would not correlate with the spectrochemical data. The state-of-the-art techniques of this equipment did allow qualitative results on individual grains or parts of grains. However, rough quantitative results based upon similar peak heights on the Kevex screen were used with caution; in the following discussions, any implication of greater precision than semiquantitative values is not intended.

The amplitudes of the peaks for one element differed from similar peaks for adjacent elements in the middle part of the periodic table, mainly because of absorption or enhancement effects. Lighter and heavier elements than the so-called transition elements did not suffer as much from these effects, and elements vertically separated in the periodic table also were less affected by these effects. Therefore, we feel that the semiquantitative data for iron ($Z=26$) and platinum ($Z=78$) indicate the amount of each element in the Pt-Fe alloy. As an example, if similar peaks for iron and platinum were of equal height, then we inferred that the alloy contained equal amounts of the two elements. If iridium ($Z=77$) was also present in this alloy, then equal heights of similar peaks for iridium and platinum probably indicated unequal amounts of each element, and the relationship to iron was impossible to assess.
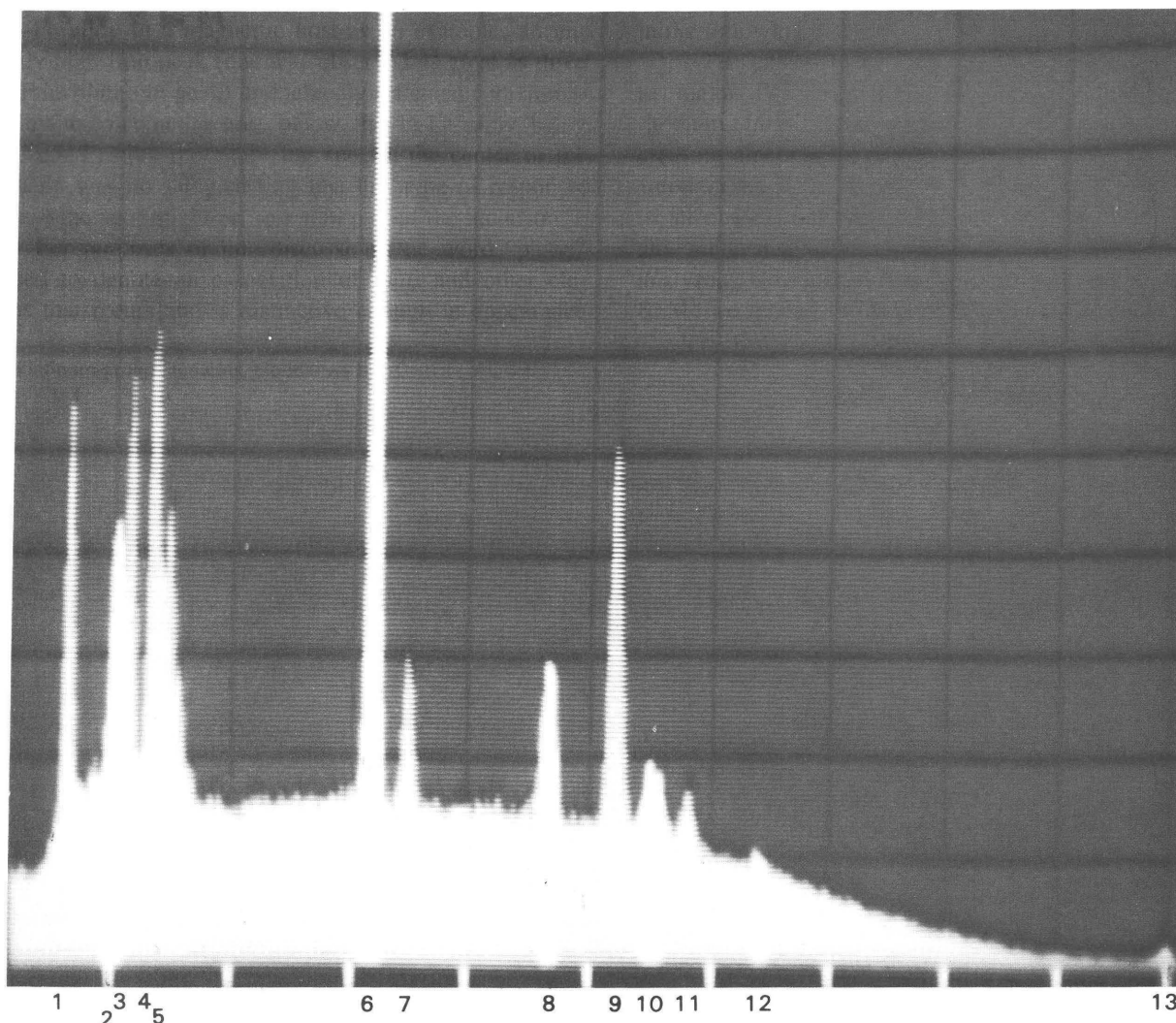
Figure 2. Photograph of the Kevex screen showing the results of analysis by the X-ray energy-dispersive system of a PGE phase. Numbers under peaks indicate (in decreasing amounts) Fe: 6,7; Rh:4,13; S: 3; As: 1,9,11; Pt: 2,8,10,12; Ag conductive coating on sample surface: 5.

A difficulty recognized in analyzing a spot near the border of an inclusion was the probability of integrating energy from the underlying host mineral. The electron beam can penetrate a thin grain and excite the material below the inclusion being analyzed, thereby causing a false impression that the inclusion contains some of the elements present in the underlying host which may be as much as 100 μm below the surface. Using an inclusion of Pt-Fe alloy in a magnetite host as an example, an unusually high iron peak (one was observed as great as three times the platinum peak) undoubtedly reflected contamination by the magnetite host below the Pt-Fe alloy being analyzed. Placing the analyzing spot in the center of the inclusion was no safeguard against this type of response, because the spot might be on a thin part of the inclusion.

For purposes of this discussion, the word "phase" is used to denote an association of PGE and other elements that recurs and is distinctive enough in appearance

and chemistry (within reasonable limits) to define what is usually called a mineral. Two associations are well known, and the accepted mineral names sperrylite and hollingworthite are assigned. Others described here are apparently new associations, and enough samples were tested to ascertain that they were distinctive and not mixtures of other minerals. The unnamed phases are called unknown A, unknown B, unknown C, and unknown D in the following discussion.

The phases to be discussed are classified according to major PGE, in the order platinum, iridium, and rhodium. In each class the elements are generally in decreasing amounts based on the amplitudes of peaks measured on the Kevex screen. Iron seemed to be ever present in all phases, but we inferred that variable amounts usually indicated contamination from below the spot analyzed. Considering the penetrative capabilities of the SEM, we tended to discount most variable shows of iron
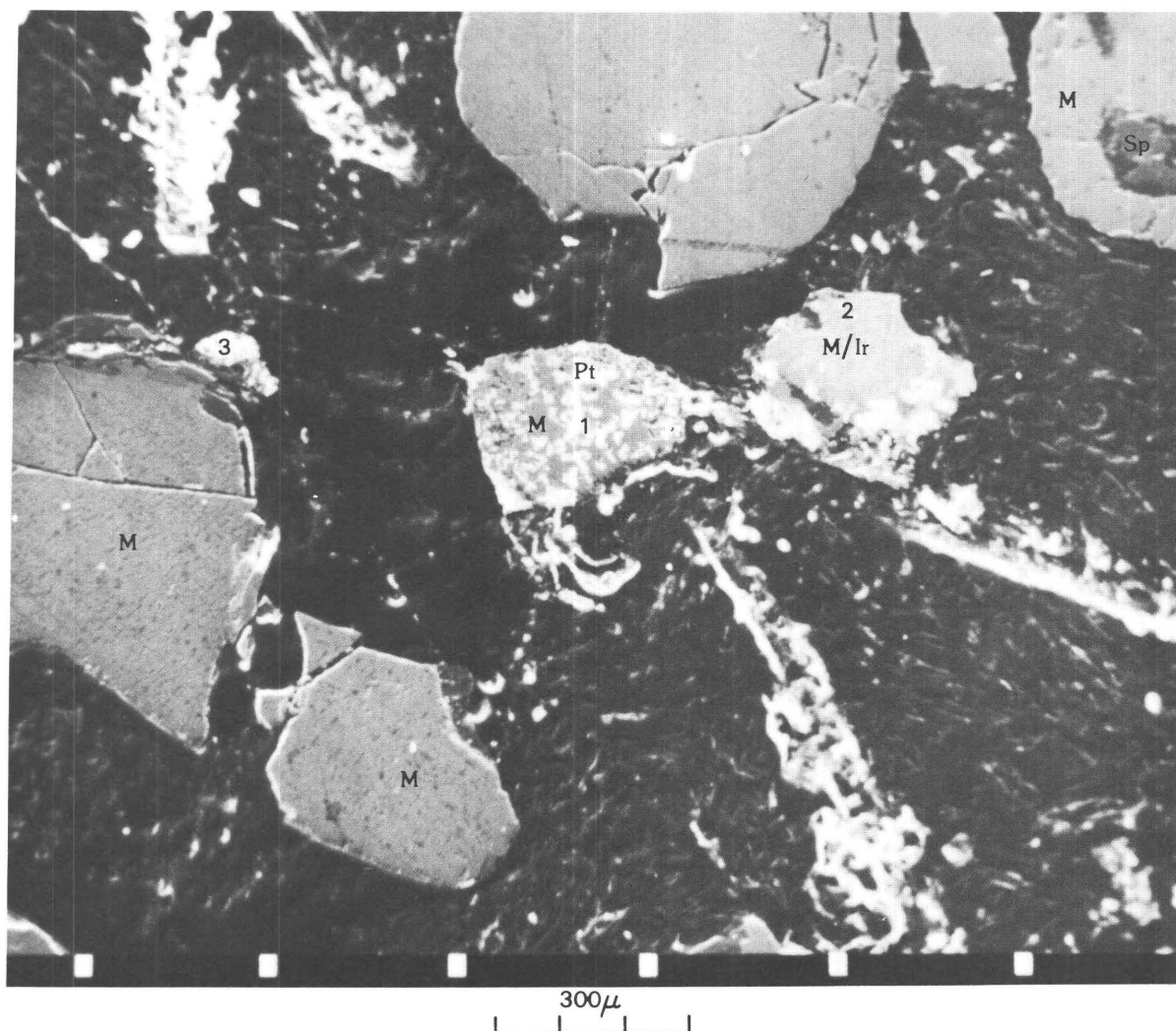
Figure 3. SEM micrograph of grains 1, 2, and 3 in polished section 69AMt14A2. Grain 1 (center) is magnetite (M) with amoeboid Pt-Fe alloy (Pt) inclusions. Grain 2 (right center) is magnetite largely covered by Ir-Fe laths (Ir), with inclusions of Pt-Fe alloy along lower border. Grain 3 is small aggregate (left center) of Pt-Fe alloy, sperrylite, and magnetite. Large grains are mostly titanomagnetite (M); small round inclusion in magnetite (upper right) is Fe-Al spinel (Sp). Dark areas are mounting medium. White lines at upper left and lower right are reflections from scratch marks. White specks on magnetite grains are mostly dust particles and some pyrite inclusions.

and to accept those that were consistent.

Pt-Fe alloy.—This was the most abundant phase observed, and it occurred as amoeboid grains between 5 and 80 μm across (figs. 3–5). A systematic test of 120 Pt-Fe alloy inclusions in grain 1 (fig. 4), using Kevex screen amplitudes of platinum and iron, showed the alloy generally contained 75 percent platinum and 25 percent iron. Several grains showed greater amounts of iron which we presumed were due to iron radiation from subjacent magnetite. This composition was similar to ferroplatinum (face-centered cubic platinum with 20–50 atomic percent iron) and to isoferroplatinum (primitive cubic platinum with composition near Pt_3Fe) as defined by Cabri (1976) and Skinner and others (1976). However, of the several minor elements listed for isoferroplatinum, in our examinations of grain 1, only rhodium, nickel, and copper were found and that was rarely and only in minute quantities. A similar composition was listed as ferroplatinum by Mertie (1969, p. 12). Thirteen electron-microprobe analyses of Pt-Fe alloy (in weight percent) were averaged: Pt, 87.97; Fe, 10.63; Rh, 0.63; Pd, 0.27; Os, 0.16; Ir, 0.0; Pb, 0.44; Ni, 0.05; Cu, 0.13; As, 0.18; and S, 0.46. These values correspond to atomic percentages: Pt, 67; Fe, 28; and S, 2. All the rest were less than 1 percent. The formula calculated for this alloy based on platinum and iron only is $Pt_{2.33}Fe$.

The terminology applied to platinum and Pt-Fe alloys has been thoroughly discussed by Cabri and Feather (1975). Since the composition of this phase is not well known, in this paper we refer to it by the general name

platinum-iron alloy, or Pt-Fe alloy, as proposed by Cabri and Feather (1975). All of the Pt-Fe alloy inclusions in grain 1 had similar compositions, but in grain 2 (see fig. 3, right center), the Pt-Fe alloy contained appreciable amounts of rhodium and arsenic, as determined by Kevex analysis, especially near the borders with inclusions containing these elements. In other polished sections of different samples, the Pt-Fe alloy contained small amounts of copper, nickel, and cobalt, but the amounts were not constant from place to place, even in a single grain. A discrete grain of Pt-Fe alloy in sample 66AMt31A6 (fig. 5) showed a range of ratios. Based on Kevex peak heights at a number of spots across the grain, we found an irregular decrease in iron and copper contents from one side of the grain to the other (fig. 5, top to bottom).

Previous descriptions of the magnetic properties of PGE alloys reveal some confusion and controversy. Mertie (1969, p. 5) pointed out that certain natural alloys of PGE are ferromagnetic, though the pure metals are only paramagnetic. Also, he indicated that the magnetic susceptibility and other physical properties of natural alloys of the PGE cannot be predicted by linear interpolation based on known proportions of their elements, and in fact, unexpected properties occur in such alloys. Magnetic properties of platinum have been cited in the literature, but the definitive reference by Palache and others (1944, p. 107) indicates that ordinary platinum is nonmagnetic or slightly magnetic. Ferroplatinum with as much as 28 percent iron is magnetic; thus it presumably may be picked up by a hand magnet. In the Tulameen River area of British Columbia, iron-rich varieties of ferroan platinum (iron was 20–50 percent, according to Cabri and Feather, 1975, p. 117) were distinctly magnetic and were capable of being attracted to a hand magnet, whereas iron-poor platinum alloys were not attracted to a hand magnet (Raicevic and Cabri, 1976).

Of the five grains containing PGE phases that we examined, three were locked with magnetite, and this explained their presence in the magnetic concentrate. The other two, in samples 66AMt7N6 and 66AMt31A6, were discrete grains with major proportions of Pt-Fe alloy. Fortuitous mechanical entrapment during screening might have accounted for the appearance of these grains in the magnetic concentrate, but more likely the iron content accounted for their inclusion in the magnetic fraction.

A number of citations on the amount of iron in Pt-Fe alloy in platinum deposits worldwide appear in the literature, and platinum has been classed into four types based on internal structure and iron content (Cabri, 1976). However, because earlier references do not use this classification, when we cite these references, we refer to platinum with appreciable iron-content as Pt-Fe alloy. A summary of compositions of platinum-bearing minerals by Wright and Fleischer (1965, p. A6) indicated a range of 2.6–28.0 percent iron in platinum. The advent of microprobe analyses of tiny platinum particles resulted in a flurry of papers which indicated averages and ranges of iron percentages in platinum or Pt-Fe alloys, as follows:

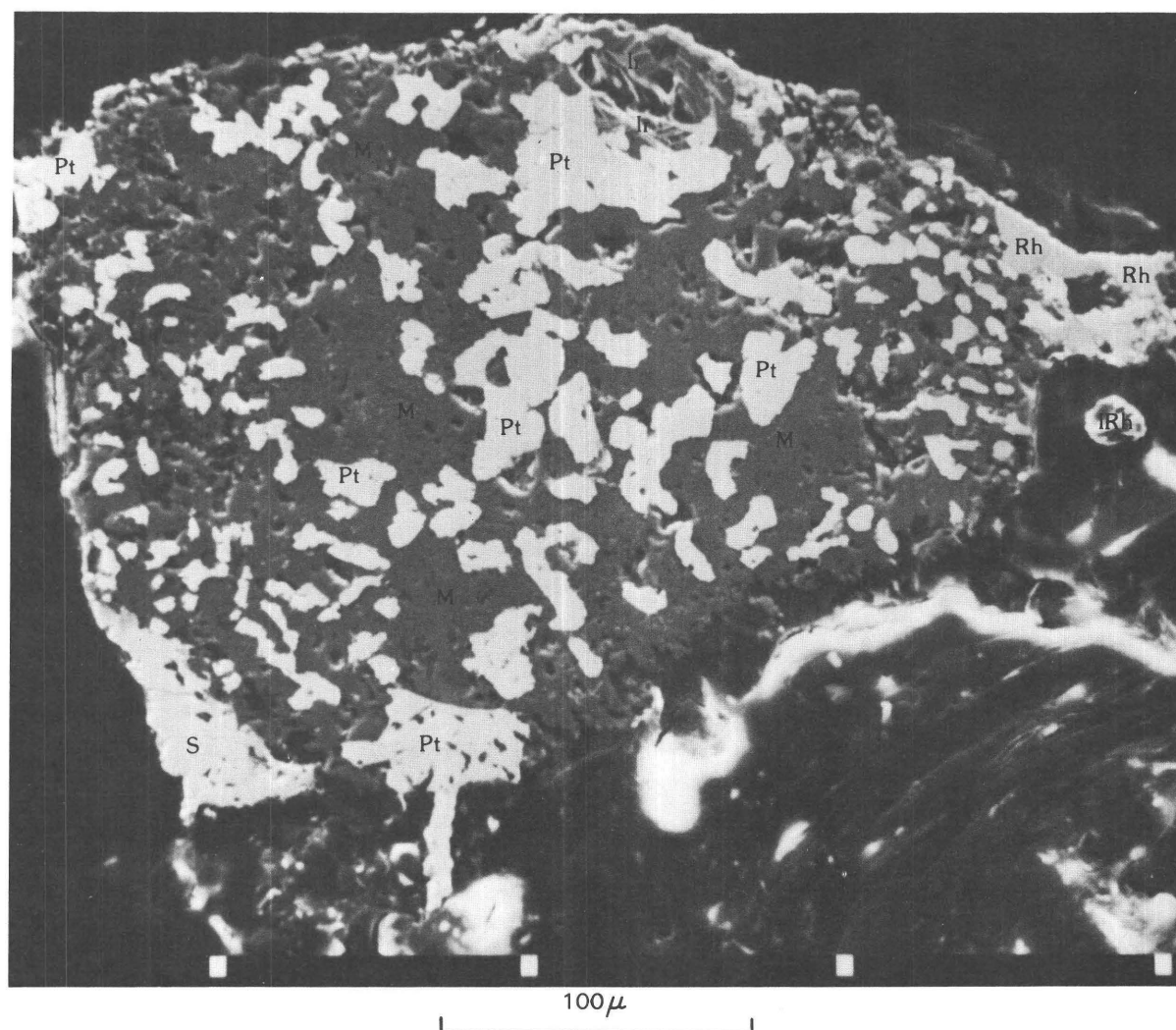| Reference	Location	Iron, in Percent
Snetsinger, 1973	Goodnews Bay, Alaska	9.5
Cabri and Hey, 1974	Tulameen River, B.C.	5.3–12.6
Cabri and Laflamme, 1974	Stillwater Complex, Mont.	9.3– 9.6
Fominykh and others, 1974	Ural Mountains, USSR	6.0– 9.2
Harris, 1974	Papua and New Guinea	8.2–10.1
Urashima and others, 1974	Yubdo, Ethiopia	9 –15
Cabri and Feather, 1975	Tulameen River, B.C.	5.4– 8.8
	Stillwater Complex, Mont.	9.6
	Similkameen River, B.C.	10.8–18.5
	Talnakh, USSR	22.8
	Anglo-American Mines, S. Africa	8.86
	President Steyn Mine, S. Africa	9.5
	Western Holdings Mine, S. Africa	5.7– 9.1
Volchenko and others, 1975	Ural Mountains, USSR	10.2
Feather, 1976	Witwatersrand, S. Africa	6.1–11.5
Raicevic and Cabri, 1976	Tulameen River, B.C.	10
Stumpfl and Tarkian, 1976	Sorashigawa, Japan	15 –25
Vermaak and Hendriks, 1976	Merensky Reef, S. Africa	0 –30
Cabri and Laflamme, 1981	Onverwacht, S. Africa	8.8–10.3
	Mooihoek, S. Africa	14.9–16.3

Figure 4. SEM micrograph of grain 1 in polished section 69AMt14A2. White amoeboid inclusions in magnetite (M) are Pt-Fe alloy (Pt). Other PGE phases are at lower left corner and upper right (sperrylite, S), upper edge (unknown A, Ir), lower right (unknown B, IRh), and upper right side (unknown C, Rh). Black areas and area with wavy reflections (lower right) are mounting medium.

Previously published photographs of Pt-Fe alloys show generally white irregular areas for this alloy (Snetsinger, 1973; Cabri and Hey, 1974; Cabri and Feather, 1975; Feather, 1976; Raicevic and Cabri, 1976; Stumpfl and Tarkian, 1976; Vermaak and Hendriks, 1976; Cabri, 1981). Photographs in Raicevic and Cabri (1976), Vermaak and Hendriks (1976), and Cabri (1981) show Pt-Fe alloy outlines that are reminiscent of Pt-Fe grains in figure 4 and are similar in grain sizes. In Feather (1976), exsolution lamellae of Pt-Fe alloy are shown as straight rods and needles 5 to 20 μm long, but this form was not reported by others nor was it seen in this study.

This study has enabled us to positively confirm the presence of the principal alloy of Mertie (1976, p. 14) in our samples from the same area. He considered this alloy as the main carrier of PGE in the Goodnews Bay

deposits. At first, the Pt-Fe alloy described here did not seem equivalent to the principal alloy of Mertie, because the compositions were not easily compared and the numbers seemed different. Mertie's principal alloy contained (in percent) Pt, about 96; Ir, 2.8; Rh, 1.1; and Pd, 0.5; iron was not reported (Mertie, 1976, p. 18). The average of 13 microprobe analyses in this study showed (in percent) Pt, 87.97; Ir, 0.0; Rh, 0.63; Pd, 0.27; Os, 0.16; Fe, 10.63; Pb, 0.44; Ni, 0.05; Cu, 0.13; As, 0.18; and S, 0.46=100.92. However, if we allow the sum of platinum, rhodium, palladium, and osmium to equal 100 percent, then the prorated percentages are Pt, 98.8; Rh, 0.7; Pd, 0.3; and Os, 0.2, values that are similar to those of Mertie's principal alloy. Likewise, if osmium and iridium equal to osmiridium alloy (Os:4Ir) are subtracted from the average of two analyses for platinum metals free
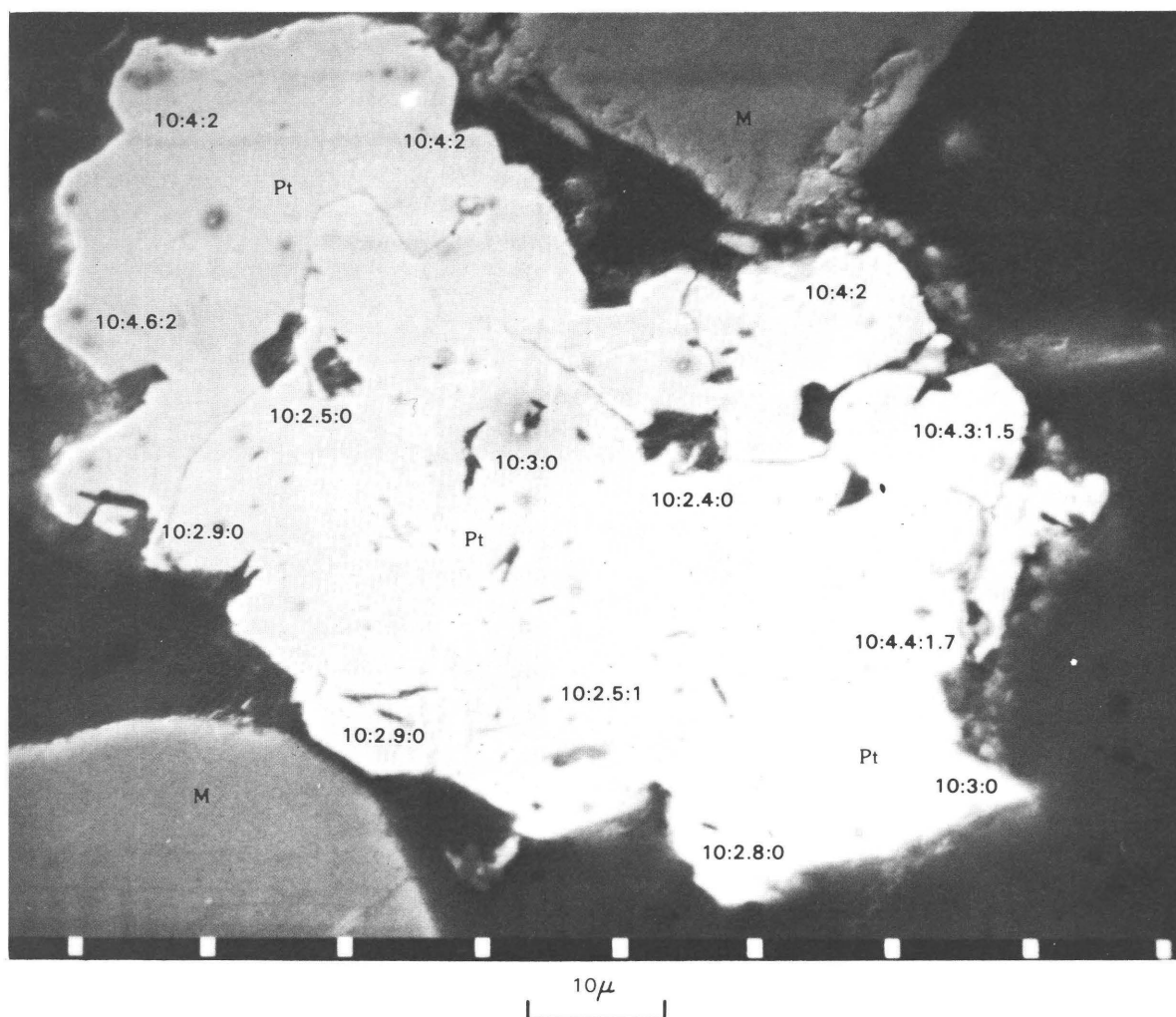
Figure 5. SEM micrograph of grain 4 (Pt-Fe alloy, Pt) in polished section 66AMt31A6. The ratio platinum:iron:copper varies from upper to lower borders. Other grains are magnetite (M), some with minor chromium and titanium. Dark-gray to black areas are mounting medium.

of gold and silver in Mertie's table 4 (1976, p. 16), then the prorated PGE and iron in Mertie's principal alloy are not too different from our average microprobe analysis of Pt-Fe alloy. The prorated percentages were Pt, 85.51; Ir, 2.82; Rh, 1.05; Pd, 0.38; Os, 0.0; Ru, 0.17; Fe, 9.45; Cu, 0.46; As, 0.05; and S, 0.11=100.00. Thus, we inferred that Mertie's principal alloy and the Pt-Fe alloy described here were similar samples.

We tested the similarity between the PGE distribution in Mertie's principal alloy and the distribution of PGE in magnetic concentrates (tables 1 and 3) via chondrite-normalized ratios (CNR) and discovered that the two distributions were alike. These ratios were computed by dividing the atomic percentages of each PGE by the atomic percentage of the same element in the average chondrite, according to estimates of abundances given by

McBryde (1972). The ratios were then plotted as logarithmic ordinates versus atomic numbers (as abscissa), the points were connected by straight lines, and the resultant curves were visually compared (fig. 6). Unfortunately, this technique suffered when elements such as osmium and ruthenium were not reported because the CNR values for the reported PGE were increased proportionately. Thus, only eight analyses (those with four or more PGE; tables 1 and 3) were used to compare with three analyses of the principal alloy given by Mertie (1976). Despite the missing osmium in all analyses and the missing ruthenium in some analyses reported in tables 1 and 3, the two sets of curves are essentially similar due to similar atomic percentages of the PGE. We accepted this evaluation as evidence of the presence of Mertie's principal alloy in the magnetic concentrates investigated in this study.
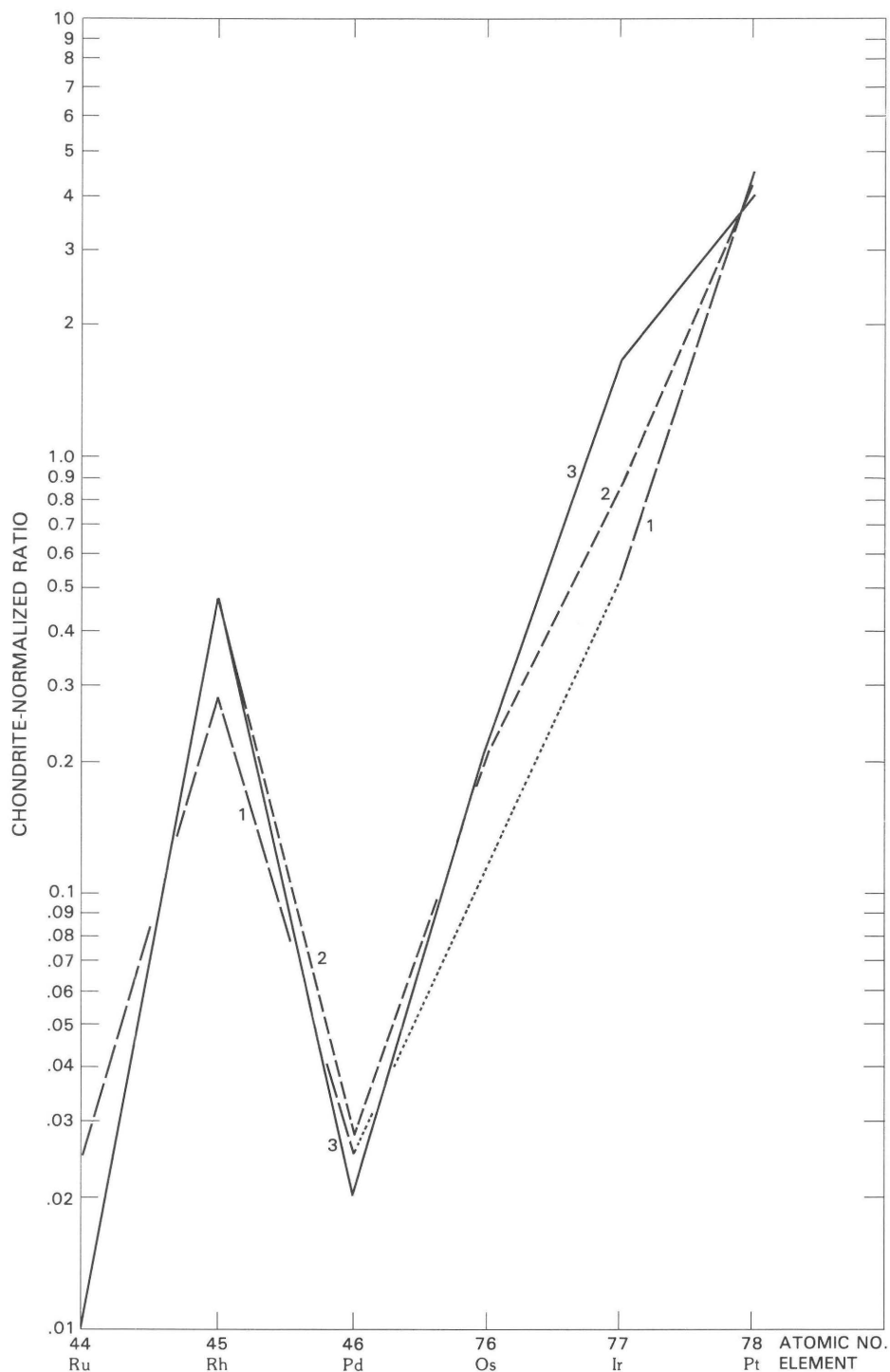
Figure 6. Graph of chondrite-normalized ratios of platinum-group elements (PGE) in three different groups of samples from the Goodnews Bay district. Curve 1: PGE in eight magnetic concentrates (this report); dotted line between paladium and iridium indicates no data for osmium. Curve 2: PGE in three sets of the principal alloy of Mertie (1976, p. 18, 21) which represent 40 samples. Curve 3: PGE production from 1936 to 1972 (Mertie, 1976, p. 22).

More conclusive proof will doubtless be attained when more complete chondrite-normalized ratios are computed from analyses of PGE that include osmium and ruthenium.

CNR plots by Naldrett and others (1979) and Hoffman and others (1979) show abscissas with PGE in

Figure 7. SEM micrograph of the lower left part of figure 4 (grain 1, polished section 69AMt14A2). Most of the large light-gray area at lower left is sperrylite (S), several small darker gray areas at the upper end of the gray area and at the lower right part are unknown C (Rh), white areas are Pt-Fe alloy (Pt), and the gray host is magnetite (M). Dark-gray area at lower edge, and with white reflection, at left, is mounting medium.

the order osmium, iridium, ruthenium, rhodium, platinum, and palladium, an order which coincides with decreasing melting points of the metals. We preferred an equal spacing of the atomic numbers of the PGE. Because of the differences in occurrence, the curves shown on figure 6 differ markedly from all CNR curves presented by Naldrett and others (1979, p. 407–408) and Hoffman and others (1979, p. 447) when they are transposed to a plot using the same abscissa as in the Naldrett and Hoffman articles. The ores in the Goodnews Bay district are mainly Pt-Fe alloys plus minor amounts of other PGE alloys, PGE arsenides, and PGE sulfides; the ores discussed by Naldrett and others (1979) and Hoffman and others (1979) are mainly copper and nickel sulfide mineralizations with minor quantities of PGE.

Sperrylite (Pt-As).—This phase was a common one found in three of the five PGE-bearing grains examined. The sperrylite tended to be slightly darker in tone than the Pt-Fe alloy (figs. 7–10). Most grains tested by Kevex analysis showed ratios of 8 parts platinum to 10 parts arsenic. These elemental proportions, plus equant forms, indicated this probably isometric mineral of platinum and arsenic was sperrylite (Wright and Fleischer, 1965; Cabri, 1972, 1976). Sperrylite was usually associated with Pt-Fe alloy and Rh-bearing minerals, and contained only platinum and arsenic except for a few border zones that show small amounts of chromium, sulfur, rhodium, palladium, and ever-present iron. The surface of Pt-As was smooth and showed no incipient cleavages; in this respect it was similar to Pt-Fe alloy.
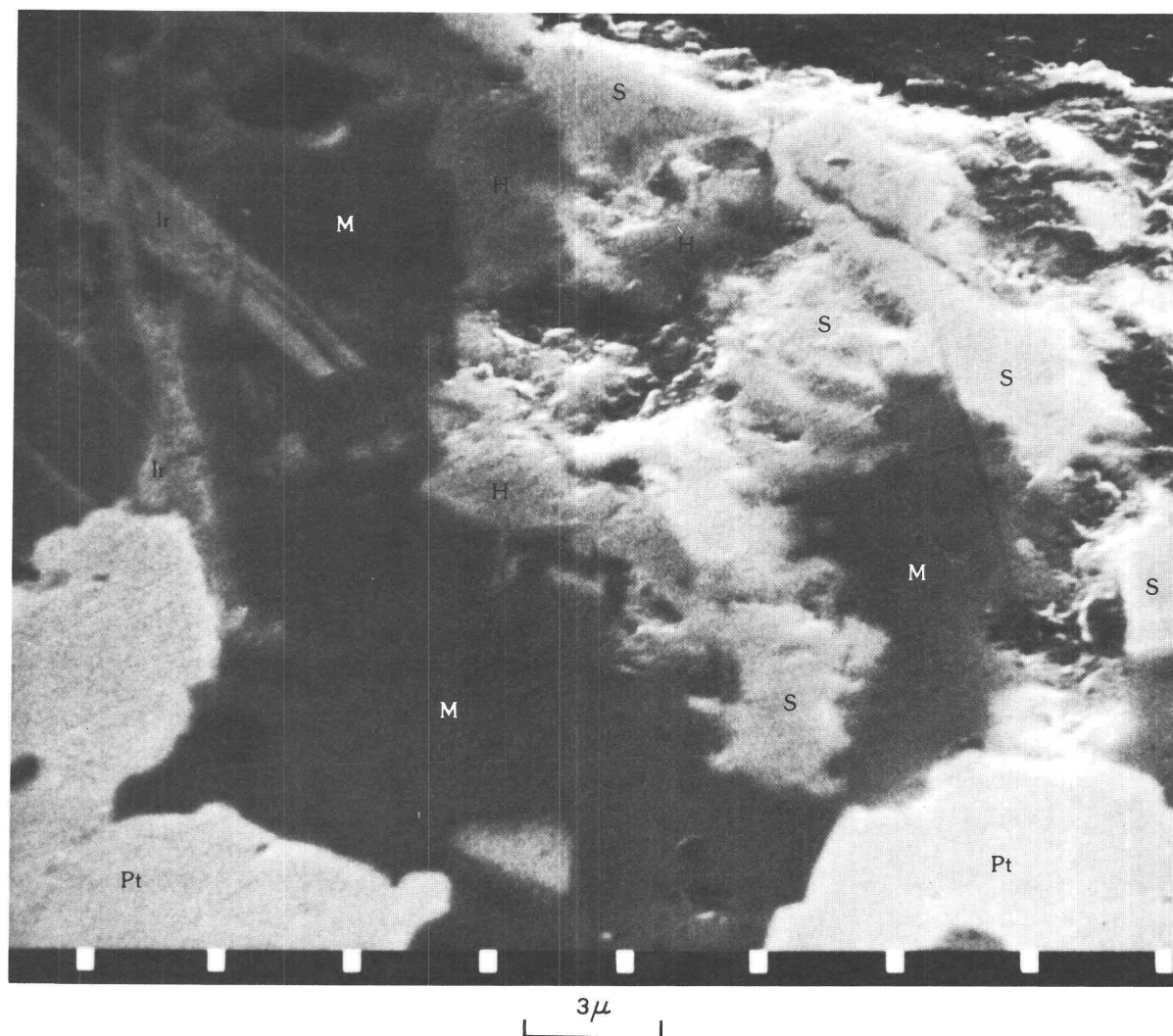
Figure 8. SEM micrograph of the upper part of figure 4 (grain 1, polished section 69AMt14A2). Most of the upper right light-gray area is sperrylite (S), the medium-gray area bordering the dark-gray magnetite (M) host is hollingworthite (H), the gray laths and fibers (upper left) are Ir-Fe alloy (Ir), and the bright grains in the lower part are Pt-Fe alloy (Pt). Black area at upper right is mounting medium.

The average of four microprobe analyses of this phase showed 54.16 percent platinum, 41.30 percent arsenic, and small amounts of other PGE, iron, lead, nickel, copper, and sulfur. Element proportions ranged from $PtAs_{1.9}$ to $PtAs_{2.1}$ and averaged $PtAs_{2.0}$ which is the formula for sperrylite.

Unknown A (Ir-Fe).—This phase was found in two of the three PGE-bearing grains in sample 69AMt14A2 where it occurred as a local clot in grain 1 and was abundant in grain 2 (figs. 4, 11, 12, 13, and 14). The form was elongate and appeared to be bladed. The average length and width were 12 μm and 1 μm, respectively; the maximum length observed was 30 μm. The blades appeared to be striated, a feature that may reflect cleavages, and many grains were bent like asbestos fibers (figs. 12 and 13). The ends of the blades were most often rag-

ged and irregular, but some were straight and at a high angle to the length, similar to terminations on monoclinic or triclinic crystals.

A Kevex spectrometer test of 50 spots along a number of bent fibers showed greater iron than iridium in 39 spots, and greater iridium than iron in 11 spots. Because of the penetrating power of the electron beam, we felt that the iron response was too high; some of it might have been from the underlying magnetite host. However, iridium is a cubic metal (Cabri, 1972, 1976, 1981), and the forms shown in figures 11, 12, 13, and 14 probably represent a noncubic alloy of iridium and iron. We presumed that iridium was more abundant than iron, but this will have to be resolved by the less powerful beam of the electron microprobe.
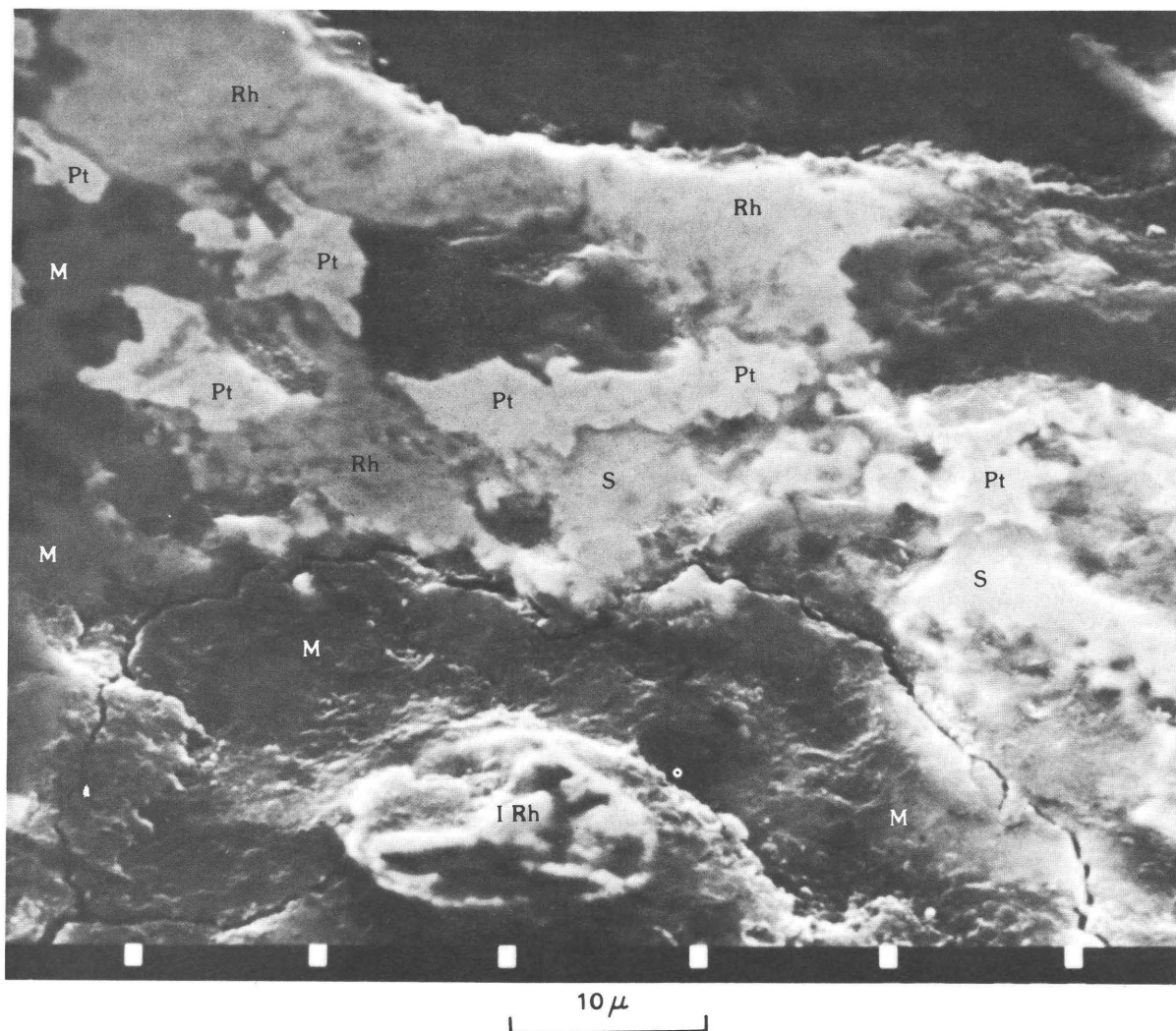
We found no previous description of this phase in

Figure 9. SEM micrograph of the right edge of figure 4 (grain 1, polished section 69AMt14A2). Much of the light-gray area in the center and right-central part is sperrylite (S), the medium-gray area in the left center and upper part is unknown C (Rh), the almost white areas are Pt-Fe alloy (Pt), and the dark-gray areas are magnetite (M). The oval area at the lower center is unknown B (IRh). The dark area along upper edge is mounting medium.

the literature. The closest reported material, composition-ally, was iridium, in which iridium was the major element and iron was one of the minor elements, but otherwise there was no resemblance between our Ir-Fe alloy and the iridium described (Cabri, 1976, p. 1477). Similar forms of PGE phases are pictured by Ramdohr (1969, p. 347, 349, 353), but iridium and iridosmium are cubic minerals, and the lamellar and tabular forms shown were probably due to exsolution along crystallographic direc-tions in the host minerals. Exsolution lamellae that strongly resemble the Ir-Fe jackstraw arrangement of laths and rods are illustrated by Feather (1976, p. 1403), but the lamellae are Pt-Fe alloy. Cabri (1981, p. 98, 106, 112, 124, 134) showed photomicrographs and described characteristic euhedral laths of iridosmine, osmium, and

rutheniridosmine that resemble the laths of unknown A, but iridosmine, osmium, and rutheniridosmine are all hex-agonal minerals that contain osmium, a PGE that is absent in unknown A. We also looked for ruthenium, but we did not find it. Other PGE phases are known with tric-linic, hexagonal, and tetragonal symmetries which could include bladed or fibrous forms, but none have iridium as a major component.

The binary compound, Ir-Fe, is hexagonal and con-tains 45 atomic percent iridium, but no physical properties are indicated by Berlincourt and others (1981, p. 24). A similar compound is indicated by Vol (1967, p. 479–480) with 50 atomic percent iridium; alloys with as much as 15 atomic percent iridium are shown as ferromagnetic; no other physical properties are cited.
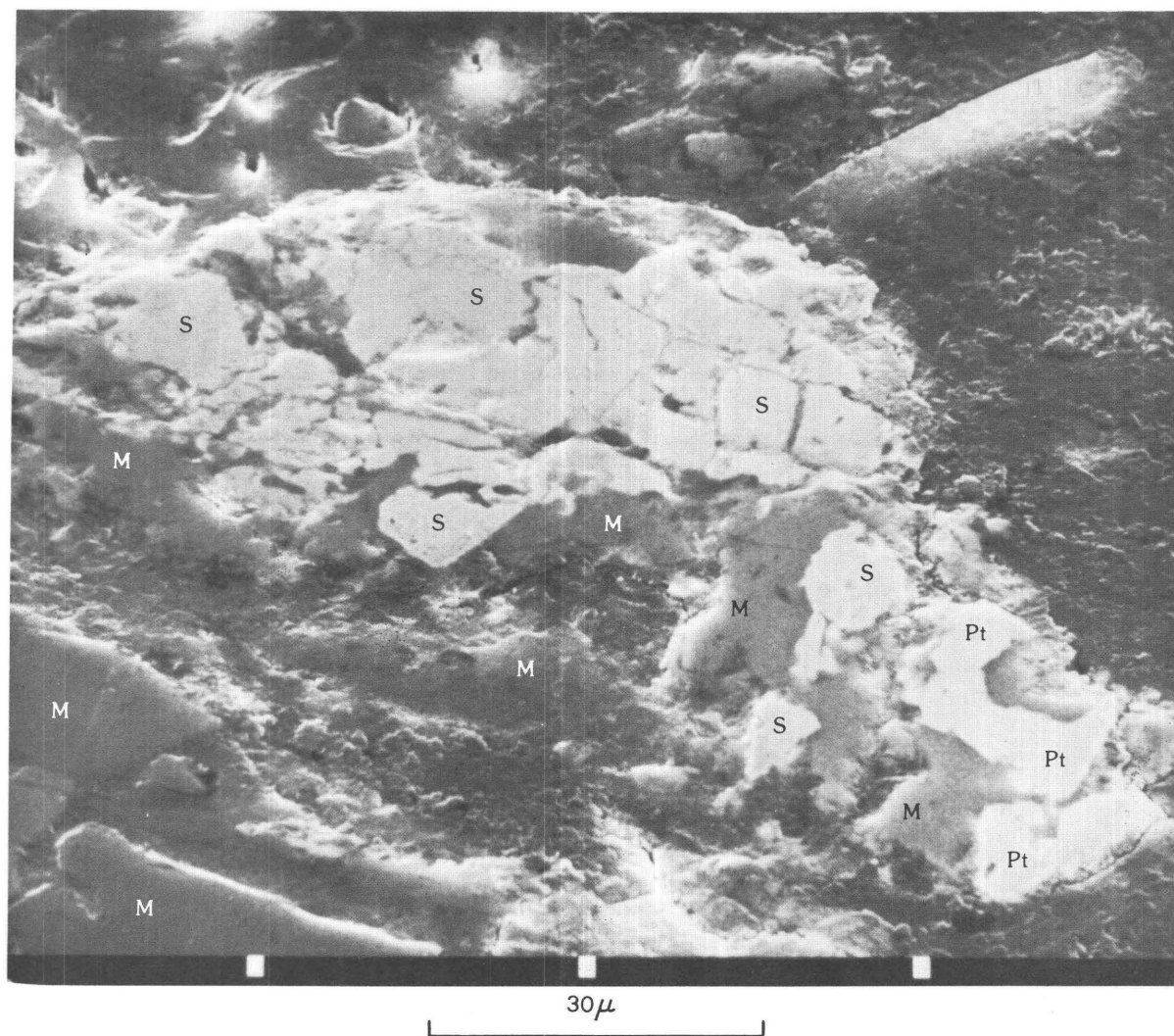
Figure 10. SEM micrograph of grain 3 in polished section 69AMt14A2. Most of the center is sperrylite (S), the bright inclusions at lower right are Pt-Fe alloy (Pt), and the gray areas are magnetite (M). The rough dark area at upper and right sides that has irregular reflections is mounting medium.

We anticipate that structural determination will be unusually difficult unless more of the Ir-Fe alloy is discovered. Microprobe analyses may determine the composition, but the grains available are too small and too intergrown with other phases to permit separation for X-ray diffraction analysis of the crystal structure.

Unknown B (Ir-Rh-Pt-Fe-As-S).—This rare phase was found as a single small aggregate (15 by 20 μm) near one side of grain 1 which is peppered with Pt-Fe alloy inclusions (figs. 4 and 9). According to amplitudes of peaks on the Kevex screen, the average of three spot analyses of this phase indicated that the relative amounts of the elements were Ir, 10; Rh, 7; Pt, 7; Fe, 3; As, 7; and S, 9. Little else can be reported because so few data are available. One of the spot analyses showed a peak height for iron of eight units, probably caused by contamination from below.

The closest chemical resemblance to unknown B that is reported in the literature is irarsite (IrAsS), in which iridium exceeds all other PGE (Cabri, 1976, 1981). However, irarsite is a cubic mineral, presumably isotropic, and arsenic generally exceeds sulfur by a factor of two to four (Cabri, 1981, p. 161). We found this aggregate to be weakly anisotropic. Thus, from chemical and physical evidence we inferred that it was not irarsite, and that it might be a new phase.

Hollingworthite (Rh-As-S).—This minor phase was found in three of the five PGE-bearing grains examined; it was mainly associated with Pt-Fe alloy (figs. 12–18). In most spots analyzed by Kevex, rhodium, arsenic, and sulfur were the only elements detected in the proportions Rh, 10; As, 5; and S, 7; but locally we found small amounts of platinum, iron, and iridium. The composition, equant form, and isotropic optics left no doubt that this
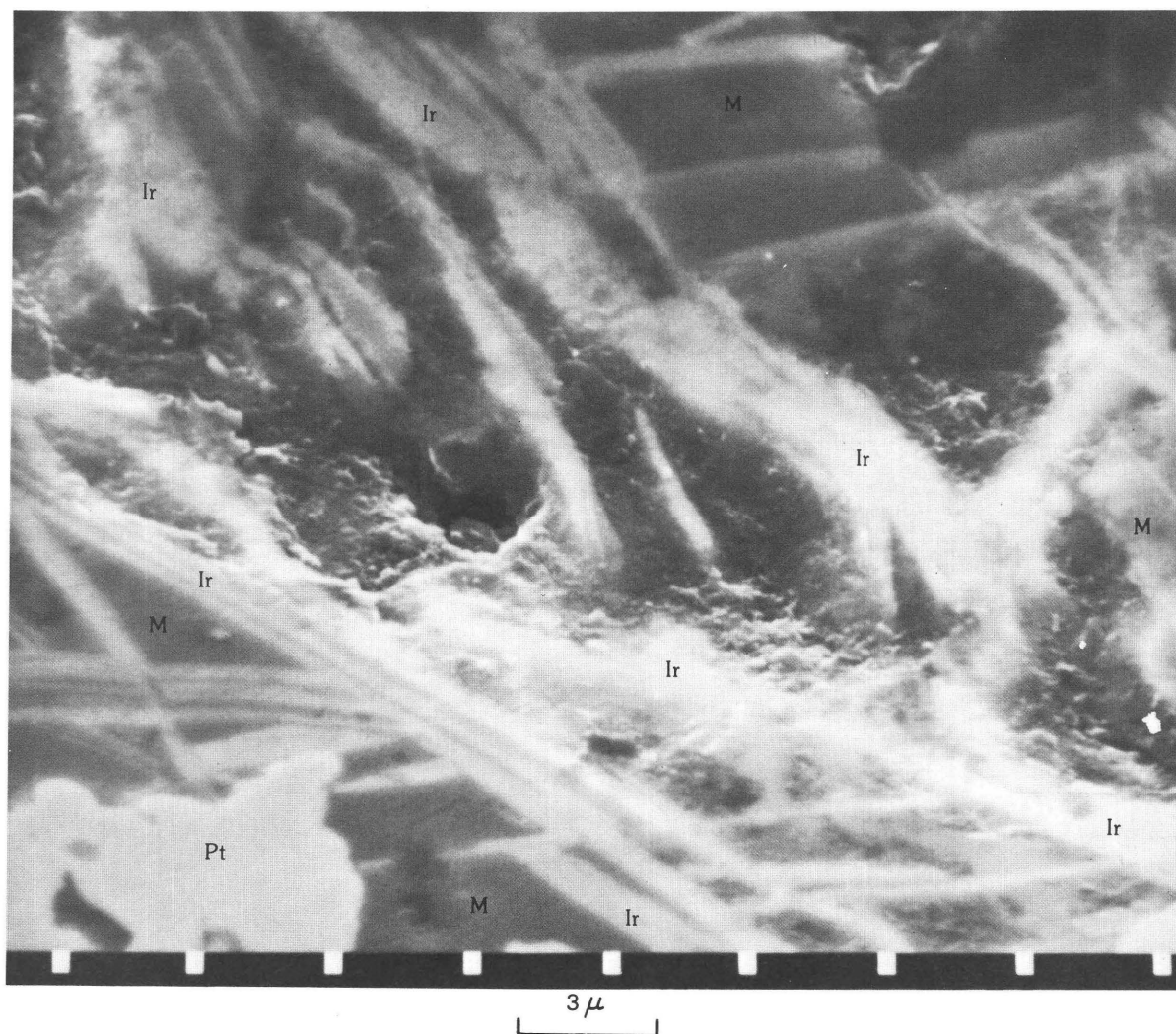
Figure 11. SEM micrograph of the upper edge of grain 1 in polished section 69AMt14A2. The laths and fibers are Ir-Fe alloy (Ir), the bright smooth area at lower left is Pt-Fe alloy (Pt), and the gray areas are magnetite host (M).

phase was the mineral hollingworthite (Stumpfl and Clark, 1965; Cabri, 1972, 1976). Grains of hollingworthite in these samples were rarely more than 10 μm long. They were irregular in form; and the surface was less bright than Pt-Fe, rarely smooth, and commonly microhummocky and pitted. Although areas of hollingworthite were similar to sperrylite in tone and reflectivity, the hollingworthite areas could be distinguished by their rough surfaces; however, borders of hollingworthite against sperrylite were difficult to see in places (fig. 17). In addition to intergrowths with Pt-Fe alloy and sperrylite, tiny hollingworthite blebs and stringers were randomly scattered in magnetite (fig. 18).

Unknown C (Rh-Pd-Ni-As-S).—This rare phase was found in only one of the five PGE-bearing grains. It was associated with sperrylite and Pt-Fe alloy, but it was slightly darker in tone than sperrylite and appeared to have a rougher surface (figs. 7 and 9). The largest area was 40 μm long and as much as 15 μm wide. This phase was similar in appearance to hollingworthite but differed in two important ways: the composition (according to amplitudes of Kevex peaks averaged for 18 spots) was Rh, 10; Pd, 8; Ni, 2; As, 4; and S, 2; and this phase was weakly, but definitely, anisotropic. The considerable amount of palladium and a lesser quantity of nickel added to the composition of hollingworthite (if such was the mode of formation of this material) served to distort the isometric symmetry to produce a nonisometric symmetry. Two preliminary electron-microprobe scans of this phase showed the following element proportions: Rh, 3, 5; Pd, 2.4, 5; Ni, 1, 1.4; Fe, 1, 3.6; As, 3.5, 6; and S, 1, 1. However, these are too few data to permit an attempt at a formula for this PGE association.

No previous description of this phase was found in the literature. The composition of hollingworthite apparently includes minor amounts of palladium and nickel
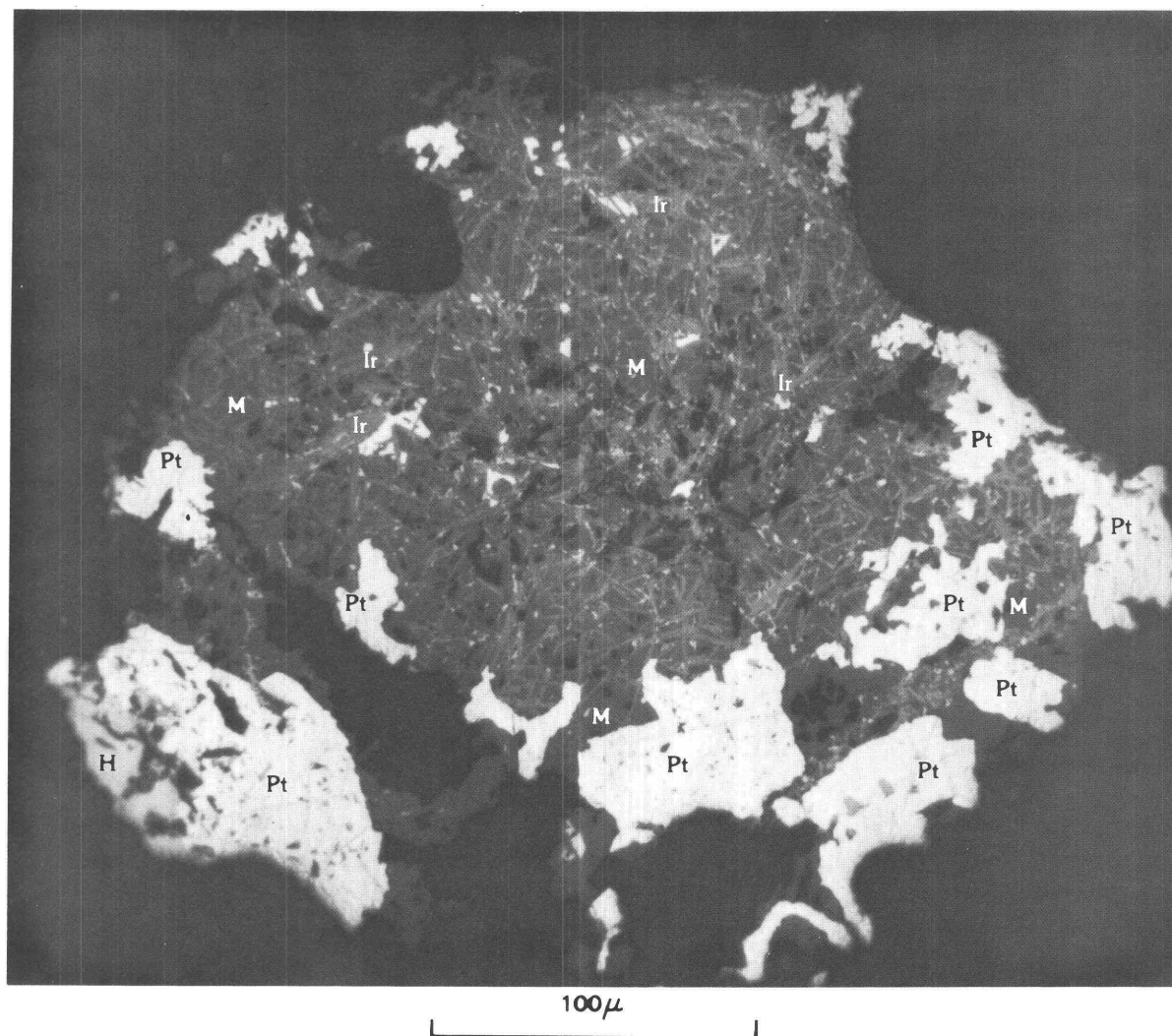
Figure 12. Photomicrograph of grain 2 in polished section 69AMt14A2. The medium-gray laths and blades are Ir-Fe alloy (Ir), the white inclusions are Pt-Fe alloy (Pt), the light-gray area at lower left is hollingworthite (H), and the dark-gray areas are the magnetite host (M). Black areas are mounting medium.

(Cabri, 1972, 1976), but no mention of anisotropic behavior was found (Uytenbogaart and Burke, 1971).

Unknown D (Pb-Rh-Fe-Ir-S).—This phase occurred in only one of the five PGE-bearing grains and was associated with Ir-Fe alloy as many tiny interstitial blebs (as much as 5 μm long) and selvages along the Ir-Fe laths and fibers (figs. 13 and 14). Pt-Fe alloy occurred as larger blebs and irregular patches that accompanied this phase as interstitial material among the Ir-Fe laths, but the Pt-Fe alloy was isotropic. This phase showed strong, but spotty, anisotropism in brown tones, and its reflectivity was less than that of Pt-Fe alloy. According to amplitudes of peaks on the Kevex screen, the average of 20 spot analyses on some of the largest blebs showed Pb, 10; Rh, 6; Fe, 10; Ir, 4; and S, 9. Iron amplitudes ranged from about 5 to 21 units of peak height, but the responses for the other elements were more consistent and

therefore yielded credible semiquantitative values.

A number of PGE-bearing phases have been known to contain lead, and most often lead has been associated with major palladium (Cabri, 1976). In one phase (xingzhongite), iridium, copper, and rhodium are major elements, lead is minor, the anion is sulfur, and the mineral is cubic. Our phase was strongly anisotropic, and the composition indicated by Kevex analysis was unlike any described in the literature. This phase will require more work to characterize the composition and structure, but because of its small size (generally less than 2 μm), both tasks will be difficult.

Other Phases

Magnetite.—Magnetite was the most abundant mineral in the magnetic concentrates under study. Most grains
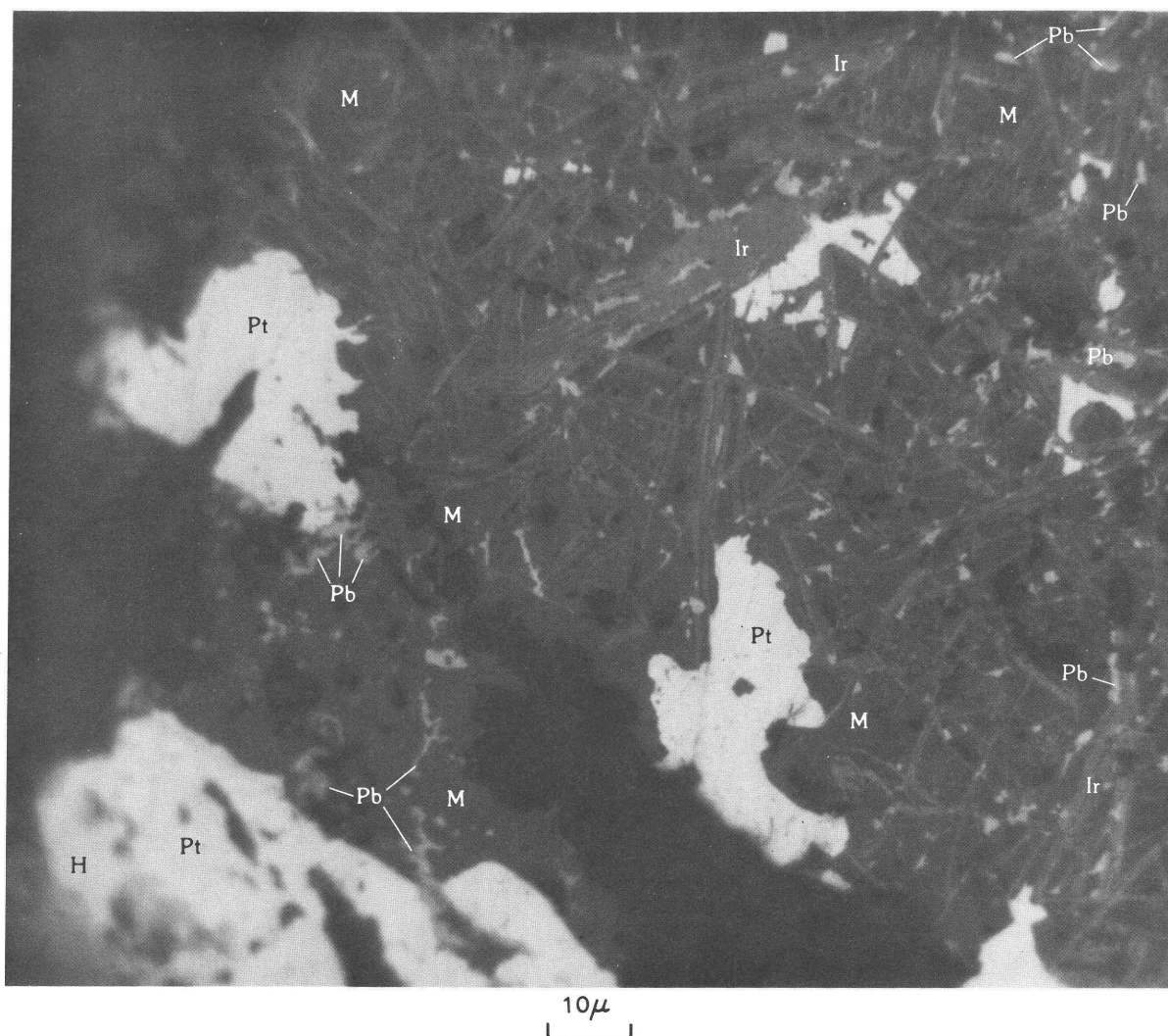
Figure 13. Photomicrograph of the left side of figure 12 (grain 2, polished section 69AMt14A2), enlarged to show (upper center) the detail of fibrous structure at the end of a lath of Ir-Fe alloy (Ir). White areas at bottom, left side, and larger interstitial areas are Pt-Fe alloy (Pt), smaller light-gray blebs are unknown D (Pb), medium-gray area at lower left is hollingworthite (H), and dark-gray host mineral is magnetite (M). Black areas are mounting medium.

in each of the size fractions were rounded and equant (fig. 3); some showed slight to extensive alteration to hematite; many had octahedral cleavage traces with exsolved ilmenite, hematite, or spinel along these traces; and some showed inclusions of, or intergrowths with, these minerals. No intergrowths with chromite were recognized, but many chromite grains had overgrowths of magnetite. In a modal analysis of 120 grains in concentrate sample 69AMt14A2, using Kevex analysis to learn the chemistry of each grain, we found the following percentages of minerals: magnetite, 89.2; ilmenite, 6.7; chromite, 2.5; spinel, 0.8; and Mg-Al-Ca-Fe silicate (pyroxene?), 0.8. Of 107 magnetite grains, 65 contained variable amounts of titanium, 8 showed aluminum, 3 had magnesium, 3 showed chromium, and 2 contained appreciable

quantities of silicon. Of eight grains of ilmenite, six had considerable manganese. Some of the magnetite was classed as titanomagnetite (fig. 3).

In addition to the above minor elements in magnetite, we discovered that platinum was held in the magnetite lattice near the borders with Pt-Fe alloy. To illustrate the platinum distribution in magnetite, we chose an area among three grains of Pt-Fe alloy in sample 69AMt14A2, grain 1, and found we could contour the platinum values across several traverses using Fe-Pt ratios according to Kevex analyses. We allowed the most prominent peak ($K\alpha_1$) for iron to reach the top of the grid chart, stopped the accumulation of data, and estimated the height of the most prominent platinum peak. The results shown by contour lines in figure 19 indicate a range of ratios from
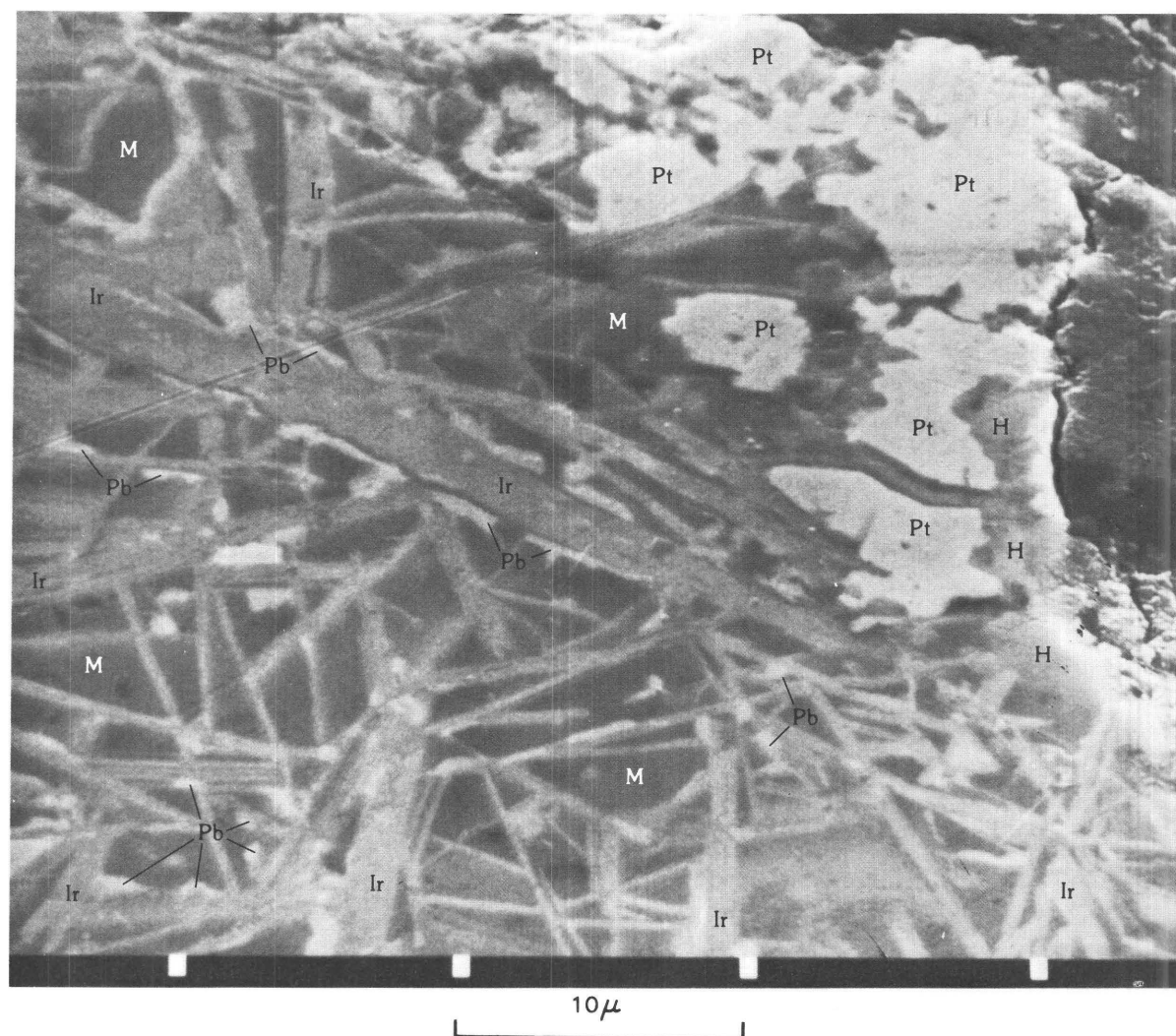
Figure 14. SEM micrograph of the upper part of figure 12 (grain 2, polished section 69AMt14A2), enlarged to show detail of the Ir-Fe laths and blades (Ir). White areas at right are Pt-Fe alloy (Pt), medium-gray areas at right edge are hollingworthite (H), light-gray interstitial blebs are unknown D (Pb), and dark-gray host mineral is magnetite (M). Dark area with irregular reflections, in upper right corner, is mounting medium.

Fe 10:Pt 0 to Fe 10:Pt 7.5. Similarly, in grain 2 of the same sample, we discovered that magnetite near the borders with PGE phases contained small amounts of rhodium and iridium. In all such border areas of magnetite, we inferred that there was a considerable amount of PGE and that such magnetite grains constitute a source of PGE that should not be ignored.

Ilmenite.—This mineral was fairly abundant among all the magnetic concentrates as discrete grains, as intergrowths with magnetite, and as inclusions and exsolution blebs in magnetite. However, in all our observations, we could find no direct association of ilmenite with PGE phases.

Chromite.—This mineral was abundant as discrete grains, but was rarely found intergrown with magnetite. In some concentrates, magnetite occurred as an overgrowth on chromite grains, and the two have been partly altered to hematite. We recognized no association of chromite with PGE phases.

Other minerals.—Less common minerals in the magnetic concentrates included pyrite, chalcopyrite, hercynite (Fe-Al spinel), and Mg-Al-Ca-Fe silicates which could not be identified under the metallographic and scanning electron microscopes. We did not detect any direct association of any of these minerals with PGE phases, nor did we analyze any concentrates of these minerals for PGE.
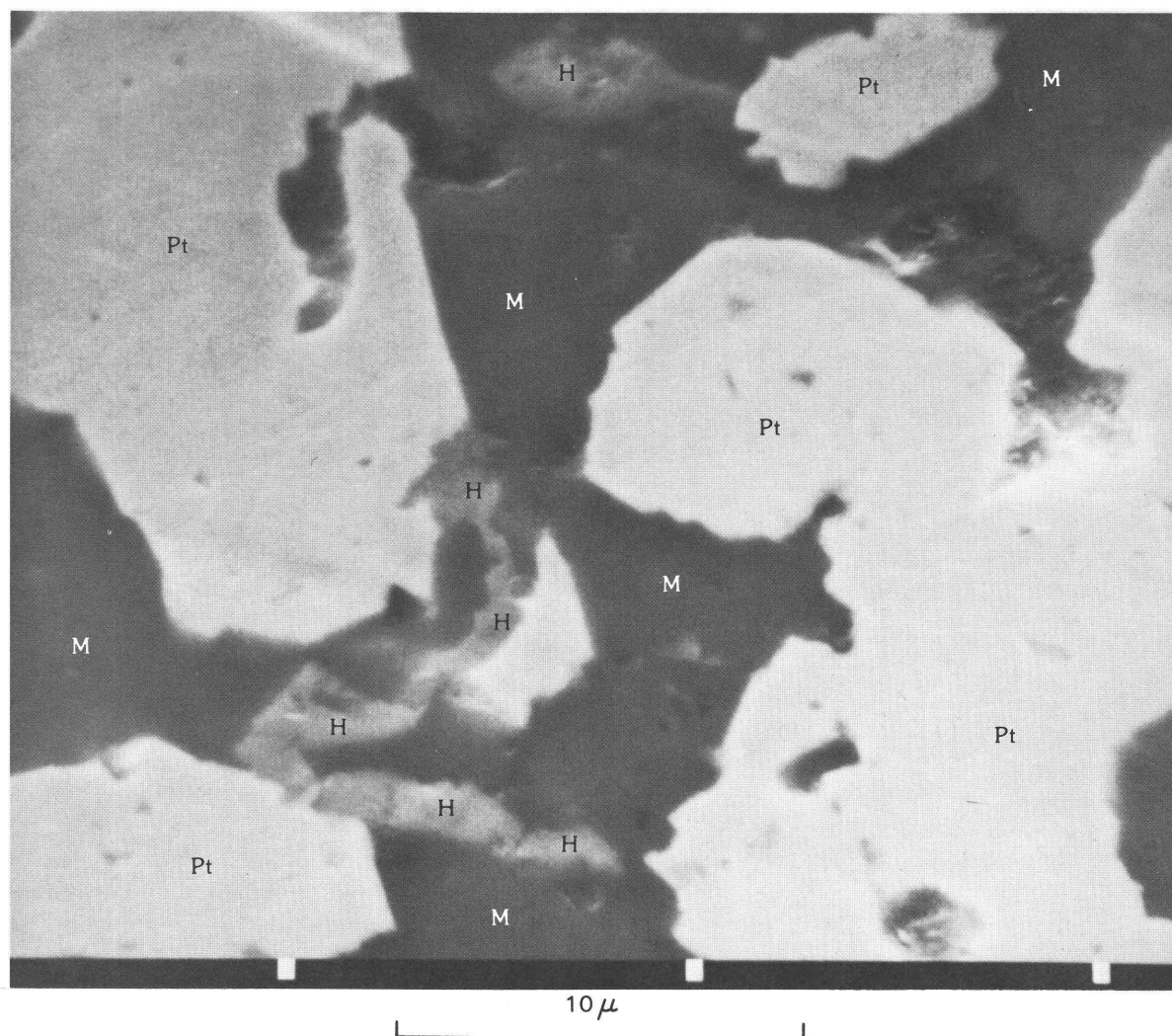
Figure 15. SEM micrograph of the center of figure 4 (grain 1, polished section 69AMt14A2). Light- to medium-gray areas in upper and lower center parts are hollingworthite (H), white areas are Pt-Fe alloy (Pt), and dark-gray areas are magnetite host (M).

CONCLUSIONS

1. We found that PGE minerals occur as discrete grains in the magnetic concentrates, that PGE mineral phases form inclusions in magnetite, and that PGE are diffused into magnetite adjacent to the borders of inclusions of PGE minerals. PGE alloys appear to range in composition, even across a single grain, so that a fixed composition is not the rule and approximate ratios can only be inferred. Mineral phases such as sperrylite and hollingworthite may have fixed compositions, but with the equipment available we could not confirm stochiometric amounts of PGE and anions from grain to grain of each species.

2. We do not know why the finest grained fractions in the screened samples contain greater amounts of

PGE than the coarsest fractions. One explanation is the possible existence of two populations of PGE phases because of two generations of PGE deposition, but nothing in the geology of the Goodnews Bay mining district is suggestive of two pulses of PGE deposition (Mertie, 1976). The source of essentially all the PGE that have been found in the Salmon River and its western tributaries is the elongate ridge known as Red Mountain, which lies west of the headwaters of the Salmon River (Mertie, 1976, p. 11). There is no evidence that the ultrabasic rocks that compose Red Mountain are a composite mass of more than one episode of emplacement. Another explanation involves uneven distribution, abundances, and grain sizes of PGE minerals in the Red Mountain pluton, but not enough is known to permit a definitive statement.
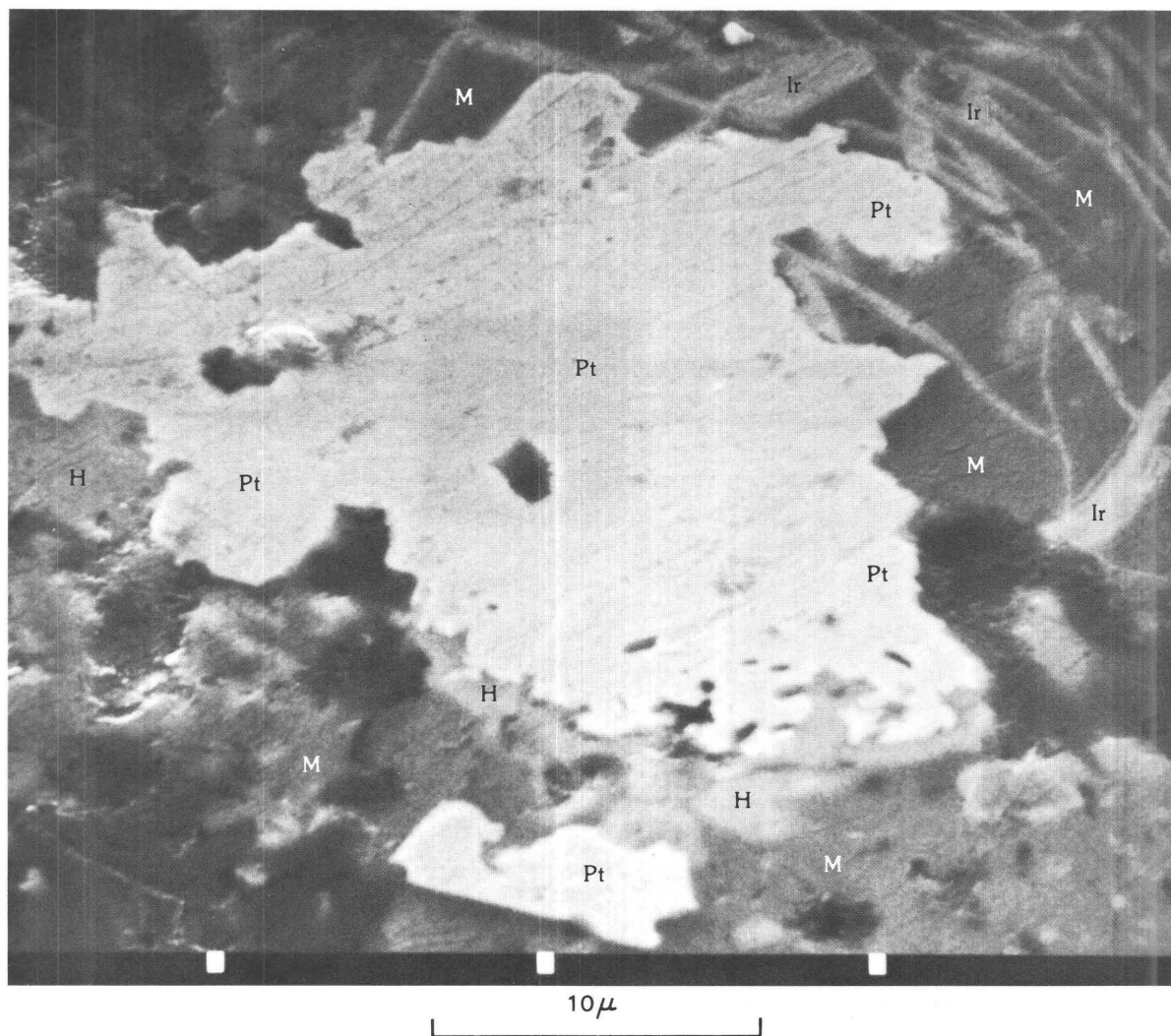
Figure 16. SEM micrograph of the left edge of grain 2, polished section 69AMt14A2. Medium-gray area at left side of almost white Pt-Fe alloy (Pt) is hollingworthite (H), fibrous forms at upper right are Ir-Fe alloy (Ir), and dark-gray areas are magnetite (M). Black areas are mounting medium.

3. We are certain that a considerable amount of PGE is located within the magnetite lattice especially near the borders with PGE mineral inclusions. Thus, these magnetite grains represent a resource for PGE, one that is easily concentrated by magnetic devices and easily dissolved in strong mineral acids to enable liberation of insoluble PGE. Mertie (1976, p. 12) has written that magnetite is known to contain small amounts of platinum metals, and that all iron ores in the Goodnews Bay mining area were crushed, milled, and concentrated to recover the contained platinum metals, but the impression received from Mertie's report is that only the inclusions were recovered. We presume that the PGE in the lattice of the magnetite might be recovered commercially as well, but this presumption must be tested empirically to learn if the benefit-cost ratio is favorable.

RECOMMENDATIONS

The study of the location of PGE in magnetic concentrates as reported here is not quite complete. The samples acquired from the Goodnews Bay mining district were easily available, and using the proper determinative tools, we located the major occurrences of PGE in the magnetic concentrates. Only a small amount of electron-microprobe work needs to be done to quantify the PGE content of the seven PGE mineral phases described here. However, we envision an expanded study of PGE in magnetic concentrates to include other areas and possibly other host minerals. Therefore, we recommend the following:
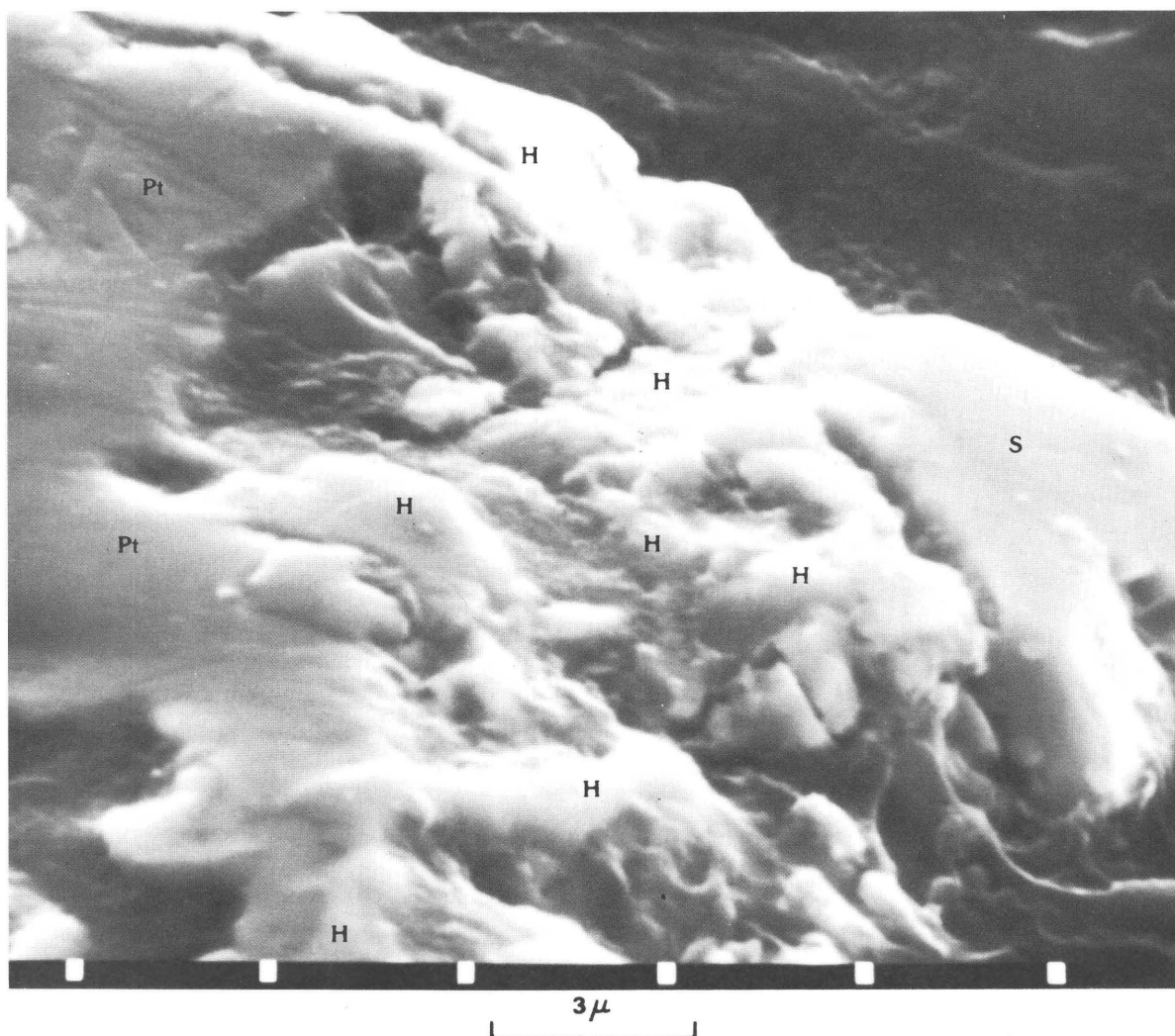
Figure 17. SEM micrograph of part of grain 5 in polished section 66AMt7N6. Rough surfaces in central area represent hollingworthite with minor platinum and iron (H), smooth area at right is sperrylite (S), and large smooth area at left is Pt-Fe alloy (Pt). Black areas are mounting medium.

1. Further study of PGE in magnetic concentrates should include electron-microprobe investigations, mainly for the quantitative chemical analysis of tiny grains which occur in the Goodnews Bay area samples. A necessary requirement will be standards for PGE in the appropriate matrix in order to quantify PGE in magnetite. If PGE are found to be intergrown or associated with chromite (Mertie, 1969, p. 87), then similar standards for PGE in chromite will be required.

2. Detrital magnetite from exploited platinum placers elsewhere in the world should be sieved to various size fractions and analyzed for PGE elements to determine if their abundances are controlled by the grain size of the magnetite, as we found for the PGE in the Goodnews Bay district.

3. Magnetite from platinum-bearing rocks and from associated mafic and ultramafic rocks should be analyzed for PGE and other trace elements to determine if their abundances in the magnetite are related to the type of rock and to the history of crystallization of the rock.

4. Similar studies should be made of magnetic concentrates from other areas where mafic and ultramafic rocks, or their eroded heavy minerals, can be sampled, including areas not now known to contain PGE. In the United States, such rocks are present in California, Oregon, and Washington on the west coast; in Montana and Wyoming in the mountainous west; in Minnesota near Lake Superior; in Appalachia along a discontinuous belt from Alabama through Vermont and including some areas in Maine (Larrabee, 1966, 1971; King and Beikman, 1974; Blair and others, 1977; Page and Tooker, 1979; Page and others, 1975); and in other
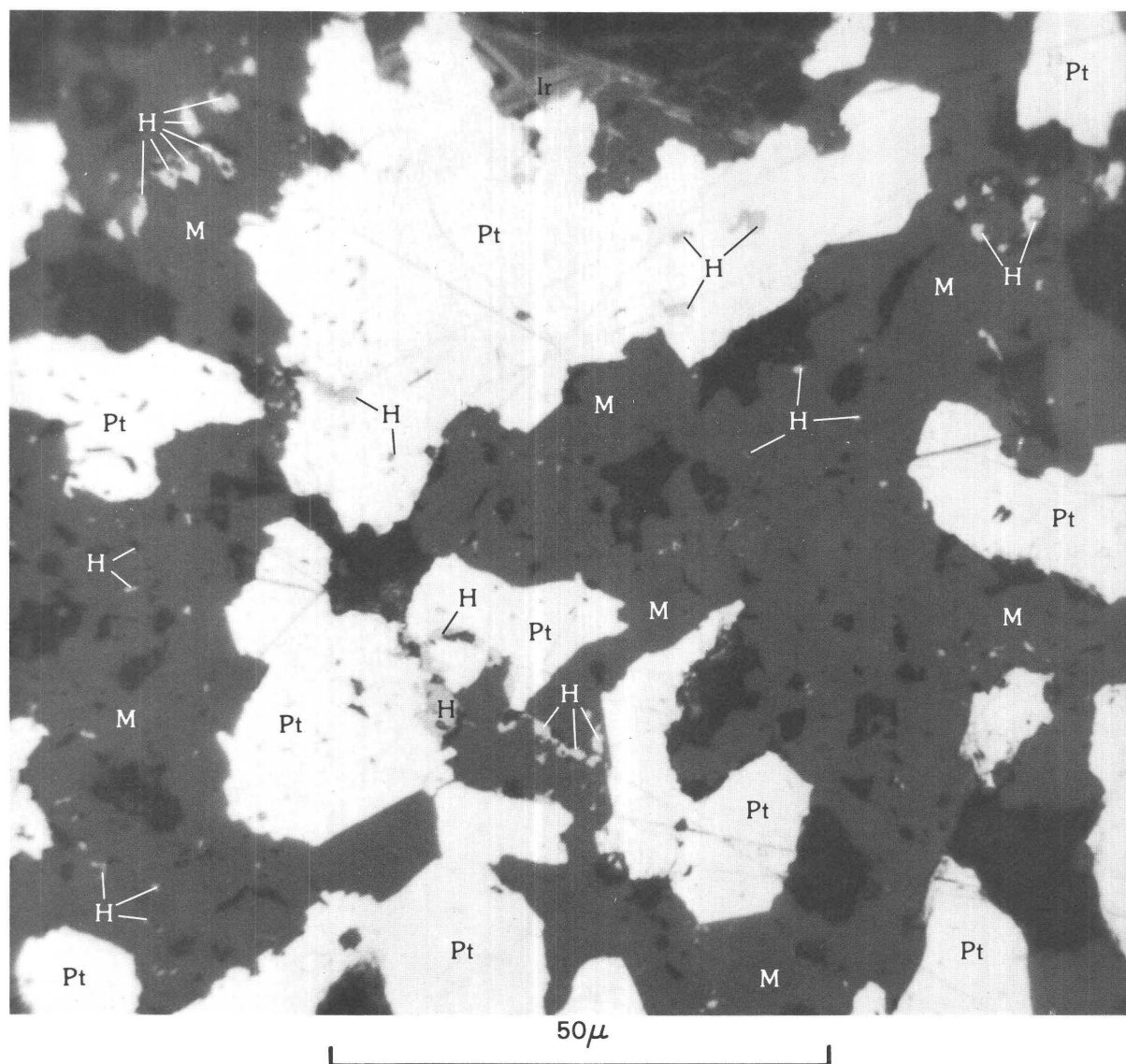
Figure 18. Photomicrograph of part of grain 1 in polished section 69AMt14A2. Small, equant, medium-gray blebs of hollingworthite (H) are scattered in or among white inclusions of Pt-Fe alloy (Pt) in dark-gray magnetite (M). Medium-gray laths of Ir-Fe alloy (Ir) are at upper edge. Almost black areas are pits filled with mounting medium.

areas in Alaska. Obviously, if PGE occur in sufficient quantities in magnetite and perhaps elsewhere in chromite (which are the common and locally abundant accessory minerals of mafic and ultramafic rocks), then these minerals represent possible sources of PGE. Lode deposits and placer concentrations could constitute significant resources of PGE as well as supply byproduct iron, chromium, and other metals (Page and Dohrenwend, 1973).

5. Study should be undertaken to develop an efficient method of getting PGE out of magnetite and into a suitable medium for analysis. Because of its scavenging character, magnetite is a good sample medium for analysis of PGE, especially for μm-sized PGE phases that could not collect in placer deposits. Magnetite is easily recovered by magnetic devices. It is easily pulverized to free the sub-μm-sized particles of PGE and to expedite solution of the PGE in strong mineral acids or absorption into the lead button of a fire assay. Although the very fine grain size of some of the particles necessitates fine grinding, the difficulties in analyzing PGE are not caused by the grain size, but rather by the long and tedious sample preparation prior to analysis. In the present preparatory scheme, the sample must be ground to a fine powder to enable early PGE ab-
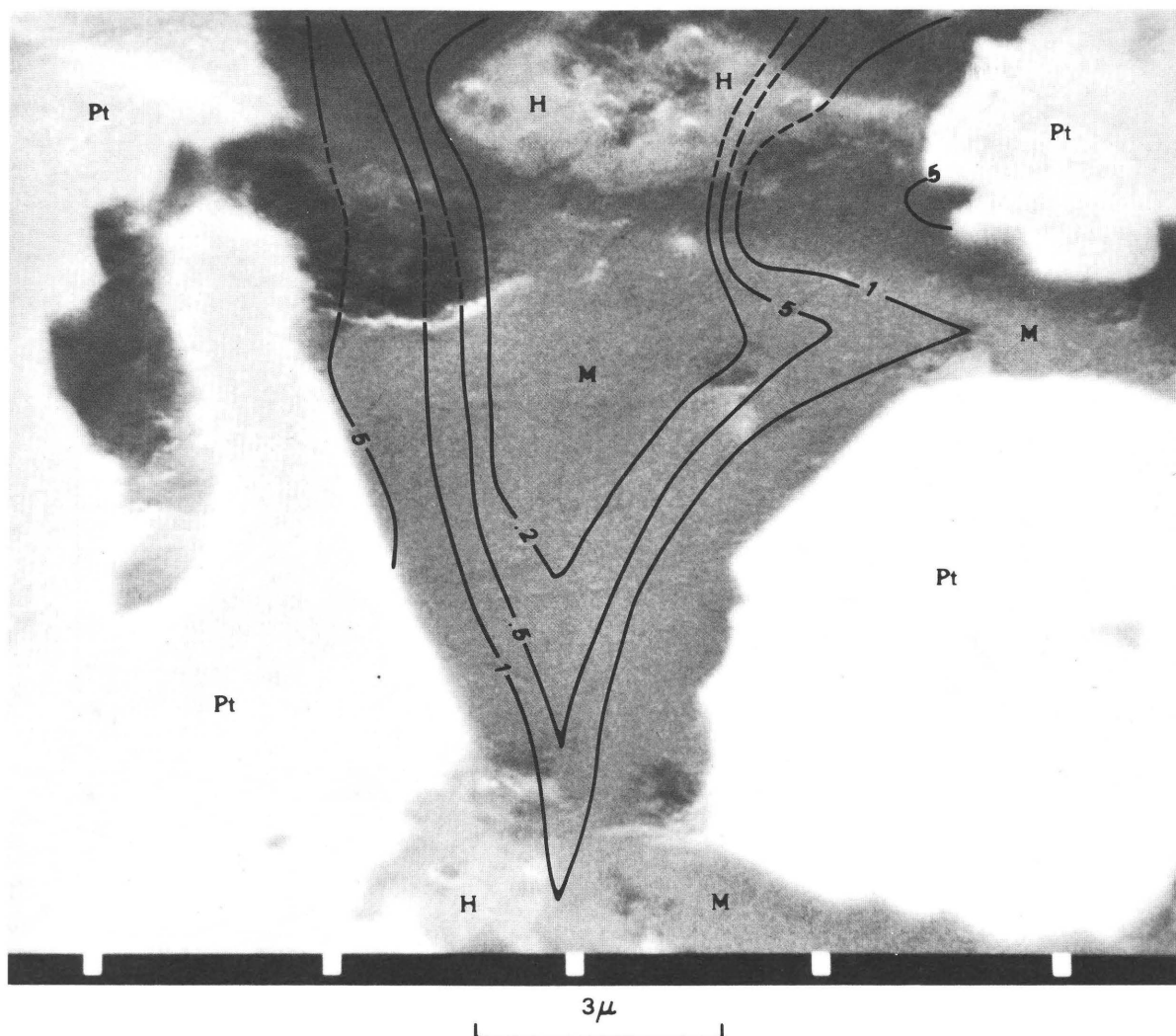
Figure 19. SEM micrograph of central part of grain 1 in polished section 69AMt14A2. Contour lines of platinum:iron ratios show that platinum has diffused into magnetite (M, dark gray) near the borders of Pt-Fe alloy (Pt, white). Medium-gray lens-like area at upper center is hollingworthite (H). Dark areas are pits filled with mounting medium.

sorption into the molten-lead phase of the fire-assay fusion. Using the present state-of-the-art techniques in spectrochemical and atomic-absorption methods of analysis to determine the parts per billion amounts of PGE in these magnetites, we found that preconcentrations of PGE between 1,000 and 4,000 times the original content are required. The fire-assay technique of dissolving the magnetite with a lead-oxide-based fusion, collecting the PGE in molten lead and concentrating the PGE by removing the lead, has proven to be a reliable method, but it requires great care and much time to yield consistent results. Perhaps a suitable chemical dissolution technique can be developed, utilizing a coarser ground magnetite powder, a suitable reagent, or a combination of reagents to take all the PGE (includ-

ing osmium) into solution, to enable use of atomic-absorption analysis with capabilities in the parts per trillion range.

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