PLATINUM-GROUP MINERALS FROM THE AIKORA RIVER AREA, PAPUA NEW GUINEA

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ABSTRACT

Platinum-group minerals (PGM) were discovered in the Aikora River area of Papua New Guinea. This area is situated in the Papuan Ultramafic Belt, in the eastern part of the island. The PGM concentrates consist almost exclusively of PGE alloys, predominantly of Os–Ir–Ru alloys (88%) and subordinately of Pt–Fe alloy (12%). Osmium (70%) is the main mineral of the Os–Ir–Ru alloys, followed by ruthenium (13%), rutheniridosmine (13%) and iridium (4%). A few grains of Os–Ir–Ru alloy are characterized by an unusually high Pt content (up to 18 wt.%), and their compositions plot in the miscibility gap of the system Os–Ir–Ru. We infer that these grains crystallized at higher temperatures. Composite grains of the various types of alloys and oriented intergrowth are very common. Laurite is the only sulfide found, as inclusions in alloys, but more commonly as a product of alteration. Sulfarsenides, undefined arsenides and probable PGE oxides are of secondary origin. The compositions of the alloys and their textures suggest a high-temperature crystallization from a sulfur-depleted Os–Ir–Ru–Rh–Pt–Fe solid solution. The PGM in the placers of the Aikora River area seem to have been derived from ophiolites of the Papuan Ultramafic Belt.

Keywords: platinum-group minerals, placer deposits, Os–Ir–Ru alloys, Pt–Fe alloy, sulfides, sulfarsenides, PGE oxides, Papuan Ultramafic Belt, Aikora River area, Papua New Guinea.

SOMMAIRE

Nous avons découvert des minéraux du groupe du platine dans la région de la rivière Aikora, dans la ceinture ultramafique papouenne de l'est de l'île de Papouasie Nouvelle Guinée. Les concentrés de ces minéraux contiennent presqu'exclusivement des grains d'alliages d'éléments du groupe du platine, surtout des alliages de Os–Ir–Ru (88%) et de Pt–Fe (12%). L'osmium (70%) est la phase minérale dominante des alliages Os–Ir–Ru; viennent ensuite le ruthénium (13%), la rutheniridosmine (13%) et l'iridium (4%). Dans quelques cas, des grains d'un alliage Os–Ir–Ru possèdent des teneurs anormalement élevées en Pt (jusqu'à 18%, poids), et leur composition se situe dans la lacune de miscibilité du système Os–Ir–Ru. Nous croyons que ces grains ont cristallisé à une température relativement élevée. Les grains composés de divers types d'alliage et les intercroissances orientées sont très courantes. On trouve la laurite comme seul sulfure dans cette suite, en inclusion dans les alliages, mais encore plus fréquemment comme produit d'altération. Les sulfarséniures, les arséniures méconnus et les oxydes probables des éléments du groupe du platine ont une origine secondaire. La composition des alliages ainsi que leurs textures font penser qu'il s'agit d'une cristallisation à température élevée à partir d'une solution solide Os–Ir–Ru–Rh–Pt–Fe appauvrie en soufre. Les minéraux du groupe du platine des graviers alluvionnaires de la rivière Aikora semblent dérivés d'un massif ophiolitique de la ceinture ultramafique papouenne.

(Traduit par la Rédaction)

Mots-clés: minéraux du groupe du platine, graviers alluvionnaires, alliages Os–Ir–Ru, alliage Pt–Fe, sulfures, sulfarséniures, oxydes des éléments du groupe du platine, ceinture ultramafique papouenne, rivière Aikora, Papouasie Nouvelle Guinée.

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INTRODUCTION

Occurrences of platinum-group elements (PGE) in Papua New Guinea are mainly known from their association with alluvial gold operations. The Aikora River area in the Papuan Ultramafic Belt and the Milne Bay Goldfield in the southeast, as well as some localities in the April Ultramafic Belt in northwestern Papua New Guinea, are reported to have yielded about 40 kg of PGE, in addition to gold, from the end of the last century to the 1930s (Grainger & Grainger 1974). Exploration by Kennecott Co. in 1984 detected significant concentrations of gold and minor PGE values in the alluvial sediments of the Papuan Ultramafic Belt and the April Ultramafic Belt. These indications prompted renewed exploration activities by a joint venture between Degussa AG (Germany) and Pancontinental Mining Limited (Australia) from 1986 to 1988. Our aim in this paper is to provide a detailed characterization of the platinum-group minerals (PGM) from the Aikora River area, discovered during this exploration activity.

GEOLOGICAL SETTING

Papua New Guinea is composed, tectonically, of three units, the so-called platform, the central mobile belt and the oceanic crust and island arcs, which are the result of the collision and accretion between the Australian and Pacific plates in the Mesozoic and Tertiary (Dow 1977). During collision, ultramafic and mafic rocks, presumably ophiolitic material, were emplaced along major fault-zones in the mobile belt and in the oceanic crust and island arcs. The April Ultramafic Belt, the Marum Ophiolite Complex and the Papuan Ultramafic Belt are the most important ophiolite zones (Fig. 1).

The Papuan Ultramafic Belt, the largest ultramafic–mafic complex on Papuan island, strikes over 400 km in a NW–SE direction, attaining a maximum width of 40 km on the northeastern side of the Owen Stanley Range in the eastern part of the island. The complex consists of a basal ultramafic zone 4–8 km thick, overlain by a gabbro zone 4 km thick and a basalt zone 4–6 km thick (Davies 1971). The ultramafic zone was subdivided by Davies (1971) into non-cumulus ultramafic rocks at the base (harzburgite, dunite and orthopyroxenite) overlain by ultramafic cumulates that contain olivine, orthopyroxene, clinopyroxene, chromite, but without plagioclase. The gabbro zone consists of cumulus gabbro formed on the transition zone to the ultramafic rocks, as well as granular gabbro and high-level gabbro. The basalt zone consists predominantly of
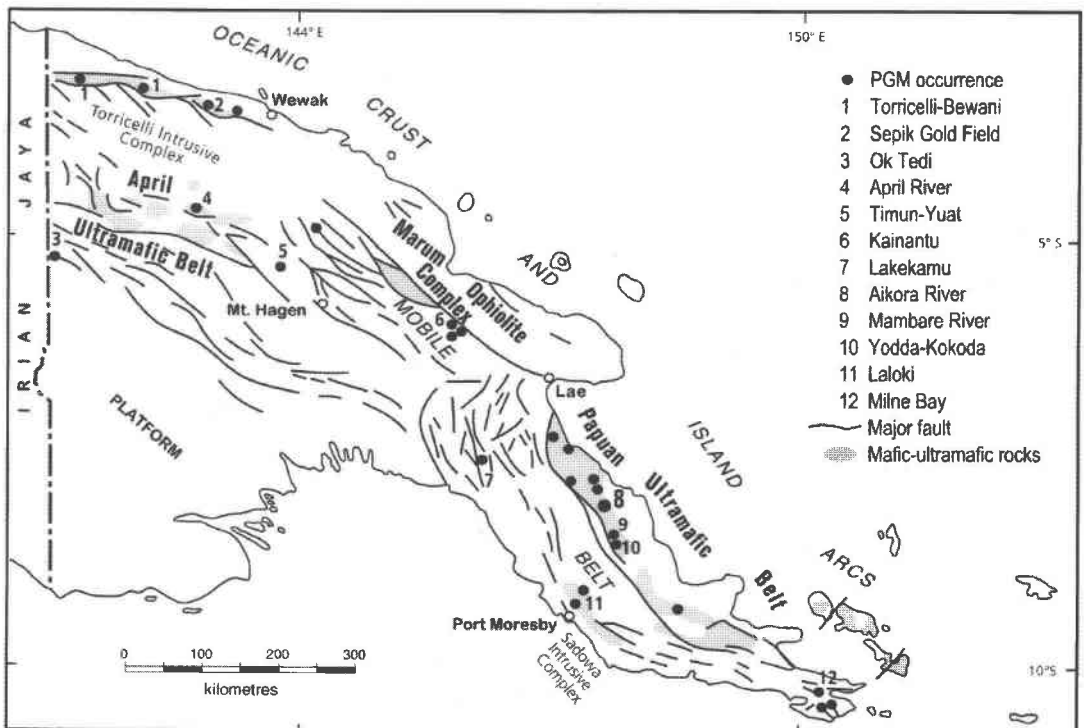

FIG. 1. Tectonic sketch-map of Papua New Guinea showing the location of ultramafic belts and PGM occurrences (modified after Power-Fardy et al. 1990).
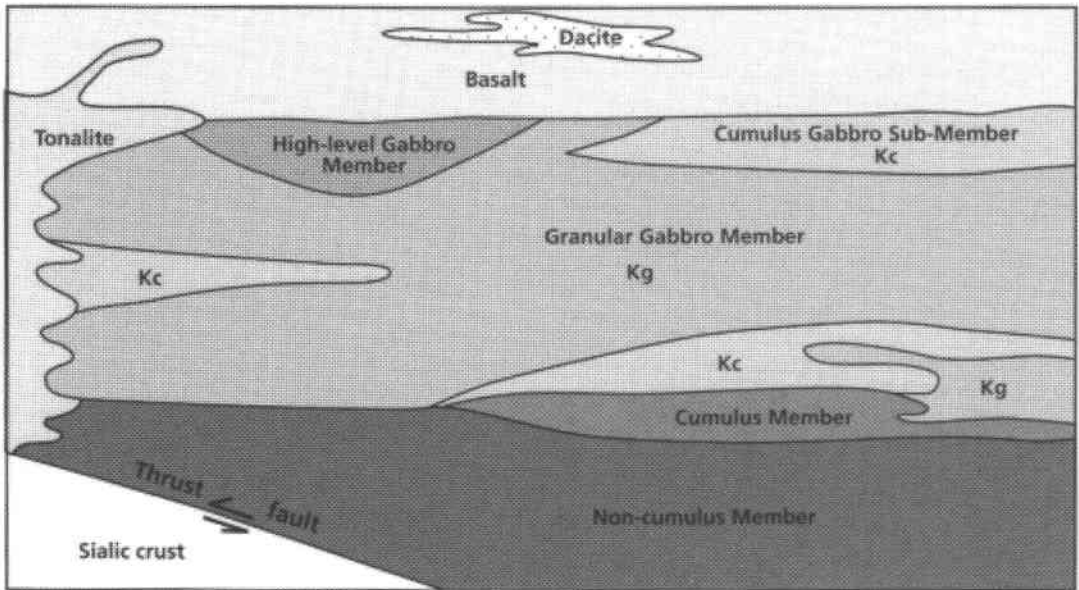
FIG. 2.   Diagrammatic relationship of Papuan Ultramafic Belt rock units (modified after Davies 1971).

massive basalt and spilitic lavas (Fig. 2). According to Davies (1971), the ultramafic zone forms part of the oceanic mantle, whereas the gabbro and basalt zones are oceanic crust.

METHODOLOGY

The Papuan Ultramafic Belt is a rough mountain area covered with dense jungle. The exploration work in the Aikora River area was extremely difficult and expensive because continuous service by helicopter was necessary. In addition to conventional methods of exploration, a special helicopter-borne sampling program was developed. The first step was the identification of a suitable airstrip for the helicopter. Rock exposures are totally absent in the area. Stream sediments were collected over a five-km-long distance along the Aikora River and its tributaries, along a section through the whole sequence of mafic and ultramafic rocks of the Papuan Ultramafic Belt (Fig. 3). The standard procedure for sampling was (i) to collect from each locality a 6-liter sample (one standard gold pan) of five mesh sand-sized sediment by sieving, (ii) reduction of the sample to approximately 100 g of heavy-mineral concentrate by panning, and (iii) visual assessment of content, size and habit of the PGM.

The heavy-mineral concentrates collected systematically along selected sections of river banks in the Aikora area were first scanned by X-ray fluorescence (XRF) to obtain an overview of the element spectrum. Subsequently, the samples were inspected with a scanning electron microscope equipped with an energy-dispersion
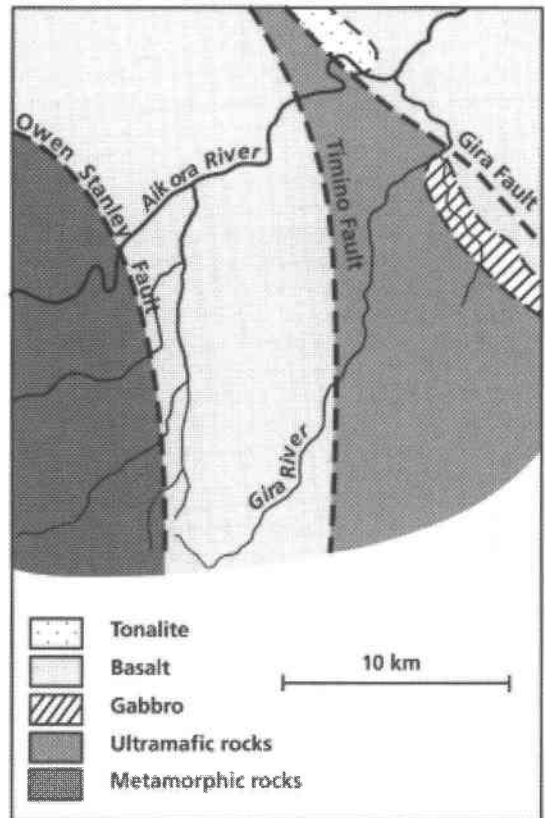

FIG. 3.   Simplified geological map of the Aikora River area.

system (SEM/EDX) to obtain preliminary information on the composition of individual grains. Grains of PGM and Au were embedded in araldite and polished with diamond powder on a Dürener polisher for optical examination and qualitative electron-microprobe analyses in the laboratories of Degussa AG (Bachmann *et al.* 1987, Bachmann 1988). The detailed quantitative characterization of the PGM was carried out recently at BGR using a CAMEBAX Microbeam electron microprobe. The analytical conditions were: accelerating voltage 20 kV, specimen current 30 nA and measurement time 10 s. The following X-ray lines and standards were used: Ru$L\alpha$, Rh$L\alpha$, Os$M\alpha$, Ir$L\alpha$, Cu$K\alpha$, Ni$K\alpha$, Se$L\alpha$, Te$L\alpha$, Bi$M\alpha$ (metals), Pt$L\alpha$, and Fe$K\alpha$ (synthetic Pt$_3$Fe alloy), Pd$L\alpha$ (synthetic PdS), S$K\alpha$ (synthetic PtS), As$L\alpha$ (synthetic GaAs), and Sb$L\alpha$ (stibnite). Raw data were corrected using the PAP program supplied by Cameca. Additional corrections were performed for enhancement of the elements Rh, Pd, Cu, As, and Sb by secondary lines. Detection limits for the elements sought are 0.1 wt.%.

One hundred and fifty-four grains of PGM were found in ten samples from the Aikora River area. In total, 935 quantitative electron-microprobe analyses were carried out on single grains and inclusions.

MINERALOGY

The main minerals in the concentrates are ilmenite, chromite and magnetite, which usually occur as euhedral to subhedral crystals up to 500 μm across. Ilmenite commonly shows exsolution lamellae of hematite. Subordinate components of the panned samples are rutile, zircon, jacobsite, pyrite and cuprite. The main silicate minerals identified by XRF are minerals of the olivine, pyroxene and hornblende groups, and epidote (Bachmann *et al.* 1987).

The gold particles are rounded and knobby, and reach up to 2 mm in diameter (Fig. 4a). There are two groups of compositions, with Au:Ag ratios (at.%) of 85:15 and 95:5. Silvery white inclusions in gold correspond to Au$_{50}$Ag$_{50}$ (Bachmann *et al.* 1987). The Au/PGM ratio varies from sample to sample, but is invariably less than 1.

The PGM are developed as well-formed crystals or rounded and flattened irregular forms (Fig. 4) and are up to 2 mm in length. Of all measured PGM, 12% fall in the class >1.21 mm, 16% between 0.91 and 1.2 mm, 42% between 0.61 and 0.9 mm, 28% between 0.31 and 0.6 mm, and only 2% are smaller than 0.3 mm. The PGM grains show a silver color with a metallic luster under the stereo optical microscope. Bachmann *et al.* (1987) identified by qualitative electron-microprobe analyses "osmiridium" and "rutheniridosmine", probably iridium, osmium or rutheniridosmine after the revised nomenclature of Harris & Cabri (1991), as the main PGM, with minor isoferroplatinum, laurite and irarsite. A quantitative assessment of the abundance of

the PGM in the concentrates is unknown. Our new quantitative electron-microprobe data show that 88% of the analyzed single grains of PGM consist of Os–Ir–Ru alloys; the remaining 12% are grains of Pt–Fe alloy. All other observed minerals occur only as alteration products in fractures or along grain margins and, to a lesser extent, as inclusions within the alloys.

Os–Ir–Ru alloys

The larger crystals of the Os–Ir–Ru alloys are mostly rounded or flattened with a lobed outline (Fig. 4a). Grains of osmium, iridium and ruthenium, but not of rutheniridosmine, smaller than 0.5 mm, show in some cases idiomorphic crystal faces (Figs. 4b, c). Crystals of Os–Ir–Ru alloy covered with Pt-Fe alloy (Figs. 4b, 6e, f) are rare. In reflected light, the grains are white with a light bluish tinge and mostly variably anisotropic depending on the orientation of the crystal. Interference colors in oil immersion change from orange to dark brown. Cubic crystals are subordinate. The majority of the grains of Os–Ir–Ru alloy are optically homogeneous under reflected light. Common inclusions comprise other PGM, composite grains of different phases in the system Os–Ir–Ru (Fig. 5a), and intergrowths with Pt–Fe alloy (Figs. 5f, 6a, b).

Electron-microprobe analyses of the homogeneous grains show the presence of all known phases of the ternary system Os–Ir–Ru. Osmium, the hexagonal alloy, with variable amounts of ruthenium, is the dominant phase (70%), followed by rutheniridosmine (13%) and ruthenium (13%). Only 4% of the analyzed crystals consist of cubic iridium and Pt-bearing iridium (Fig. 7). The compositions of the grains show a well-developed trend parallel to the miscibility gap in the system Os–Ir–Ru and confirm similar observations by Harris & Cabri (1973) on material from Papua New Guinea of uncertain origin. This trend also is in good agreement with compositions of material from Burma (Hagen *et al.* 1990) and from the Urals, Russia and Alberta, western Canada (Cabri *et al.* 1996). Figure 7 shows also that the majority of the compositions cluster on the boundary between osmium and rutheniridosmine, close to the triple point. It is typical of all analyzed grains of Os–Ir–Ru alloys that the content of Pd is nearly always below the detection limit. Only a few grains carry up to 0.4 wt.% of Pd.

The grains of osmium are mostly homogeneous and contain up to 1.0 wt.% Pt and 3.0 wt.% Rh. Compositions vary between 34.8 and 80.1 at.% Os, 8.3 and 41.0 at.% Ru, and 5.0 and 39.3 at.% Ir. The most abundant inclusions are idiomorphic or drop-like grains of Pt-Fe alloy up to 15 μm across. Also common are oval, roundish inclusions of ruthenium, iridium, and rutheniridosmine. An unusual polygonal intergrowth of osmium and Pt–Fe alloy was observed in one grain (Fig. 5c). Some grains also contain small euhedral inclusions of chromite.
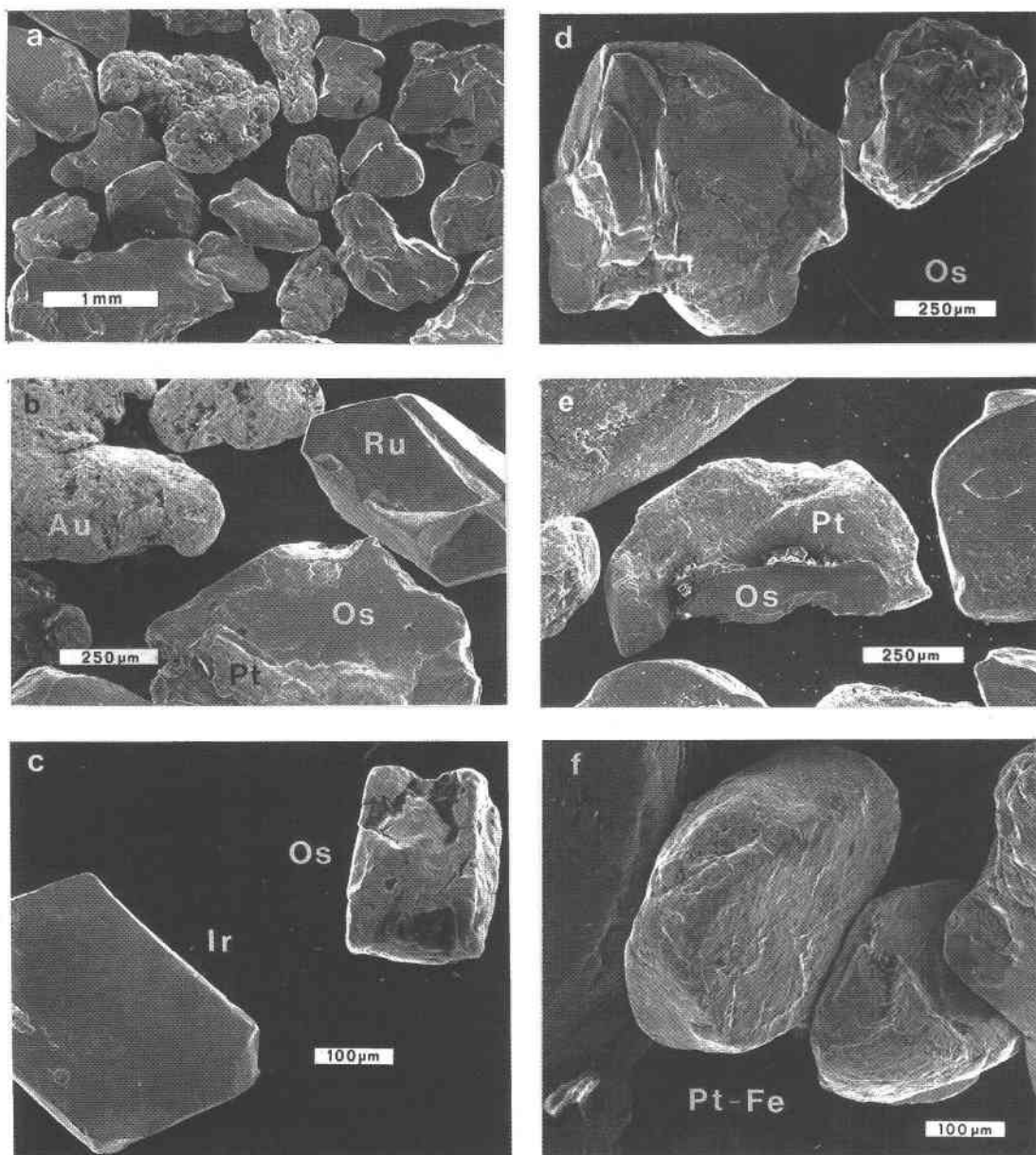
FIG. 4. SEM photomicrographs of PGM from Papua New Guinea. a. Concentrate of PGM and gold (knobby). b. Euhedral crystal of ruthenium, anhedral grain of osmium covered with Pt–Fe alloy, and knobby grains of gold. c. Euhedral grains of iridium and osmium. d. Osmium with partly preserved crystal faces. e. Rounded grain of Pt–Fe alloy intergrown with osmium. f. Pt–Fe alloy with partly preserved crystal faces.

Ruthenium also is mostly homogeneous and carries up to 5.5 wt.% Pt and 2.0% Rh. Compositions range from 33.8 to 63.2 at.% Ru, 9.5 to 42.3 at.% Os, and 11.9 to 33.6 at.% Ir. The only inclusions found are tabular euhedral and parallel oriented needle- or schlieren-like grains of Pt–Fe alloy 10 μm across (Fig. 5d). Like

osmium, ruthenium may be intergrown with Pt–Fe alloy at the margin of grains.

Rutheniridosmine has compositions between 16.7 and 31.8 at.% Ru, 26.4 and 41.2 at.% Os, and 35.5 and 42.1 at.% Ir, and contains up to 2.0 wt.% Pt and 1.0% Rh. Long tabular grains or large parallel laths of Pt–Fe
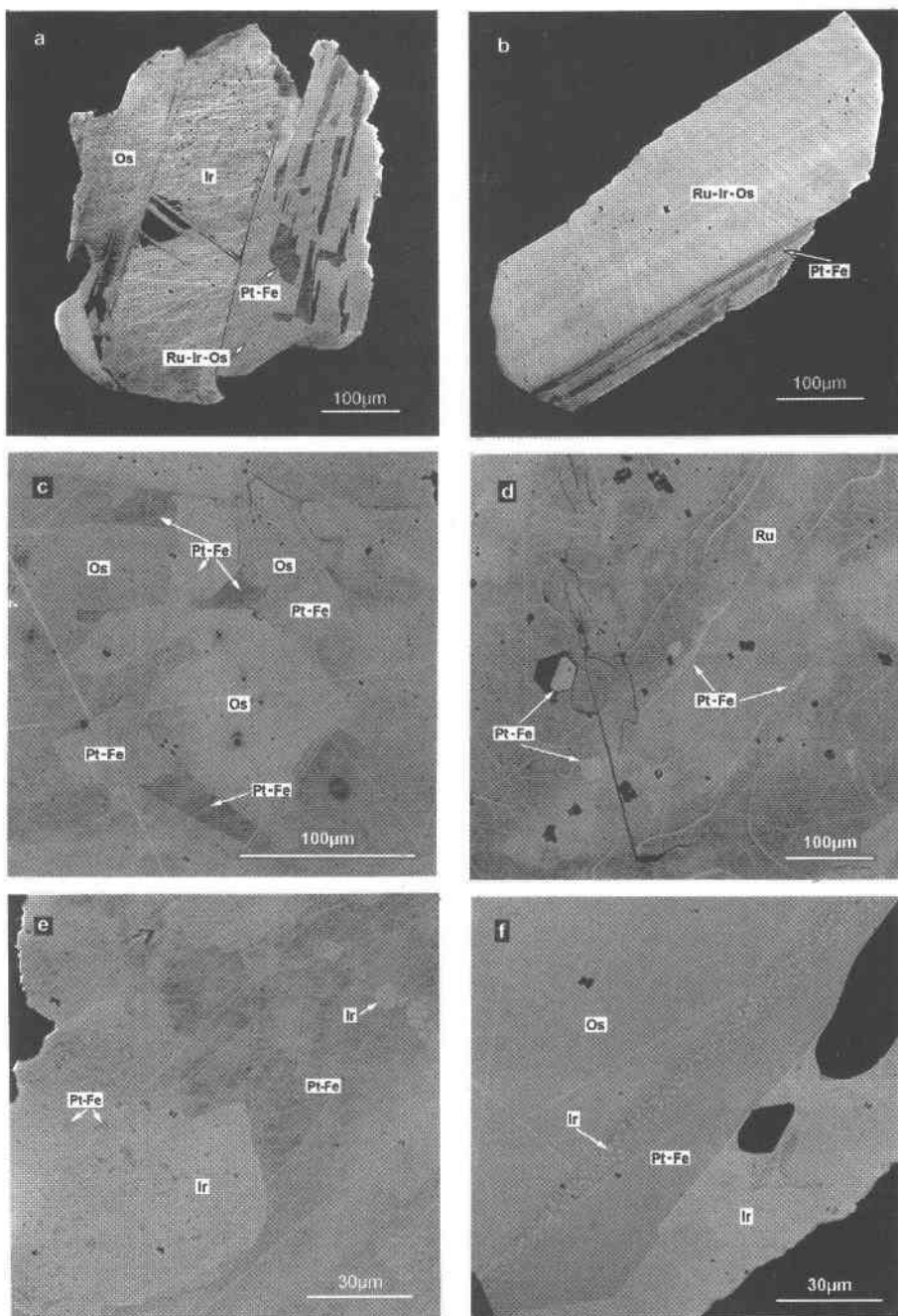
FIG. 5.   Back-scattered electron images (BEI) of PGE alloys from Papua New Guinea. a. Composite grain of osmium (Os), iridium (Ir), and rutheniridosmine (Ru–Ir–Os) with lamellar inclusions of Pt–Fe alloy (Pt–Fe). b. Tabular grain of rutheniridosmine (Ru–Ir–Os) with parallel laths of Pt–Fe alloy (Pt–Fe) near the margin. c. Polygonal intergrowth of osmium (Os) and Pt–Fe alloy (Pt–Fe). d. Ruthenium (Ru) with euhedral inclusions and schlieren-like exsolution-induced domains of Pt–Fe alloy (Pt–Fe). e. Intergrowth of iridium (Ir) with drop-like inclusions of Pt–Fe alloy (Pt–Fe), and Pt–Fe alloy (Pt–Fe) with euhedral to anhedral inclusions of iridium (Ir). f. Composite grain of osmium (Os), Pt–Fe alloy (Pt–Fe) and iridium (Ir), with drop-like oriented exsolution-induced domains of iridium (Ir) in Pt–Fe alloy at the boundary with osmium (Os).
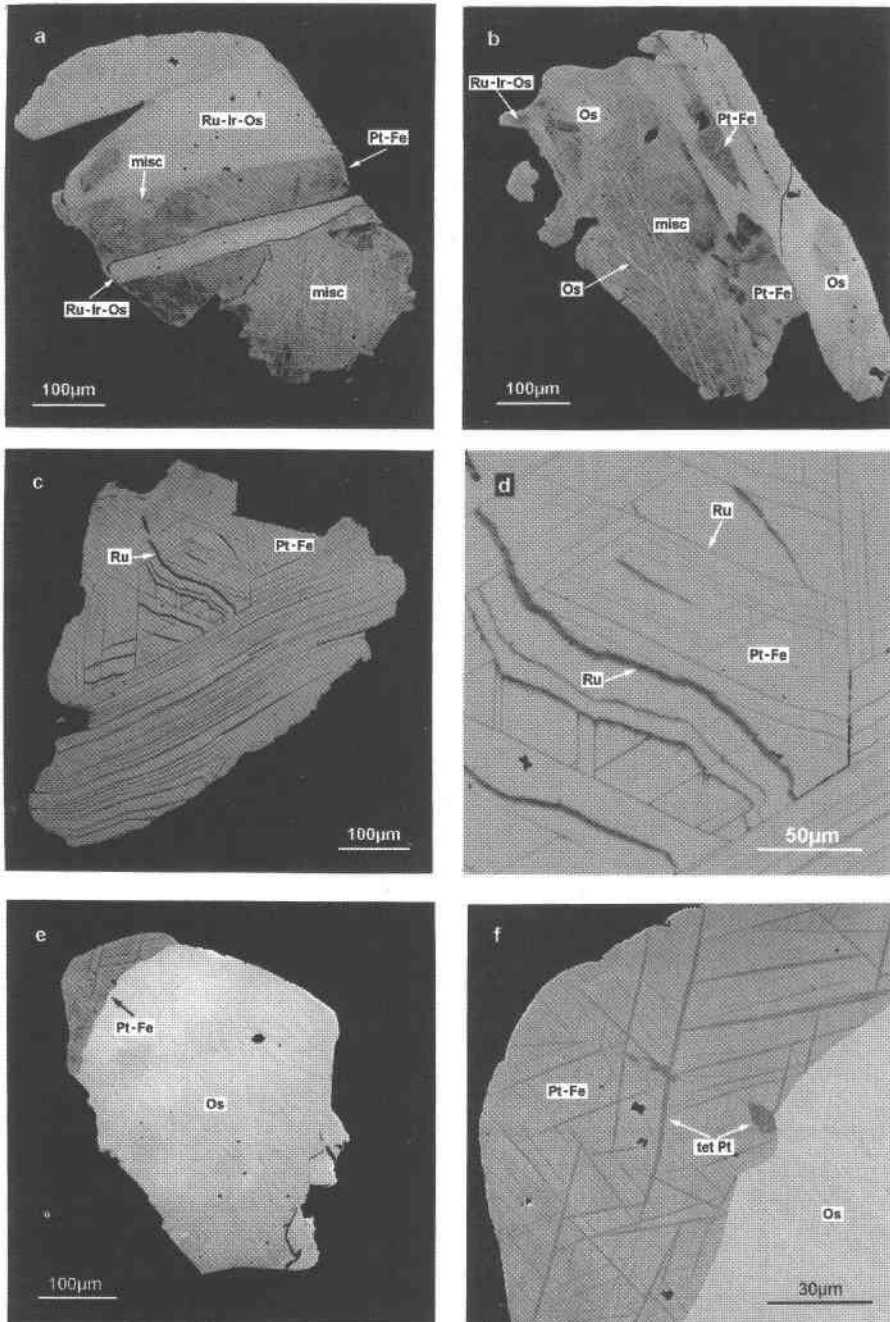
Fig. 6.   Back-scattered electron images of PGE alloys from Papua New Guinea. a. Composite grain of rutheniridosmine (Ru–Ir–Os), Pt–Fe alloy (Pt–Fe), and an Os–Ir–Ru alloy with a composition that falls in the miscibility gap (misc) in the ternary system. b. Composite grain of osmium (Os) with inclusions of Pt–Fe alloy (Pt–Fe), and Os–Ir–Ru alloy with a composition in the miscibility gap (misc) and with oriented exsolution-lamellae of osmium (Os). c. Pt–Fe alloy (Pt–Fe) with oriented exsolution-lamellae of ruthenium (Ru). d. Close-up of the crystallographically oriented exsolution-lamellae of ruthenium (Ru) in top-left portion of (c). e. Osmium (Os) covered with Pt–Fe alloy (Pt–Fe) with oriented exsolution-lamellae. f. Close-up of the top-left portion of (e) showing crystallographically oriented exsolution-lamellae of tetraferroplatinum? (tet Pt) in Pt–Fe alloy matrix (Pt–Fe).
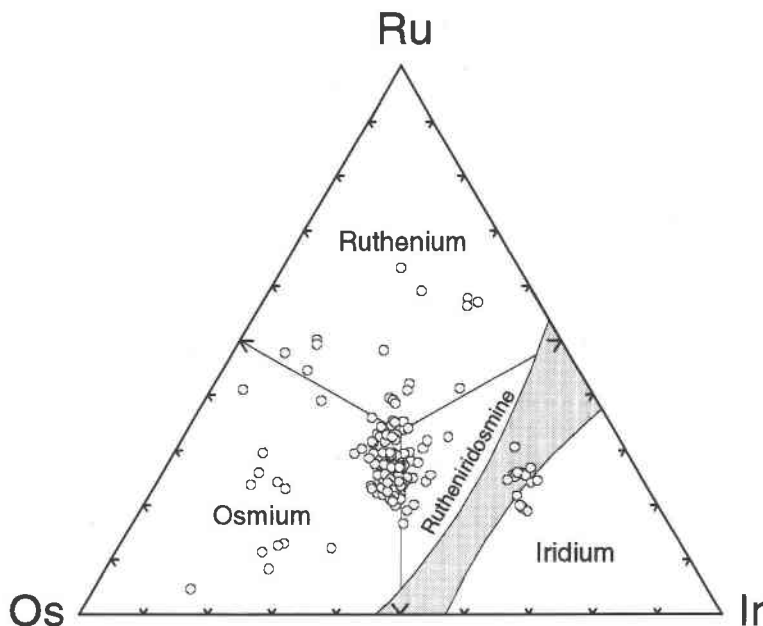
FIG. 7. Triangular plot showing electron-microprobe compositions of Os–Ir–Ru alloys. The shaded area represents the miscibility gap proposed by Harris & Cabri (1991) and its modification by Cabri *et al.* (1996).

alloy occur in some grains or near grain boundaries (Figs. 5a, b). Composite grains with iridium or Pt–Fe alloy are very common. Chromite and chalcopyrite occur as rare inclusions.

Grains of iridium are invariably intergrown with the Os–Ir–Ru alloys (Fig. 5a) or Pt–Fe alloy (Figs. 5e, f). They show little variation in composition (58.6 to 61.3 at.% Ir, 16.4 to 21.3 at.% Os, 19.0 to 24.6 at.% Ru) and

normally carry up to 9.0 wt.% Pt and 1.8 wt.% Rh. In some grains, the Pt content is higher than the amount of Os. Therefore, the compositions plot in the ternary system Ir–Ru–Pt (Table 1, no. 3/13). Iridium occasionally contains small blocky or elongate inclusions of Pt–Fe alloy, which mostly show a preferred orientation in the host mineral (Fig. 5e).

Some composite grains of Os–Ir–Ru alloys and Pt–Fe alloy show areas of different brownish colors under reflected light after carbon-coating, as well as different brightness in back-scattered electron images (Figs. 6a, b). Electron-microprobe analyses of these areas gave compositions in the miscibility gap of the system Os–Ir–Ru (Fig. 7), in a narrow field between 52.5 and 56.9 at.% Ir, 22.0 and 30.6 at.% Ru, and 16.4 and 21.1 at.% Os. All compositions contain between 8 and 18 wt.% Pt, but only traces of Fe (Table 1, no. 7/33, 7/37, 7/44). Also, some grains of osmium contain drop- or schlieren-like areas of the same composition. This was earlier observed by one of us (TWW) on material from the Urals and was also recently described by Krstić & Tarkian (1997) from Yugoslavia. These mineral grains could have been formed at higher temperatures. On the other hand, we contend that the miscibility gap discovered by Raub (1964) in the system Ru–Ir and by Rudman (1967) in the system Os–Ir is only applicable to Pt-free systems, and that the presence of Pt may stabilize the phases in that part of the system Os–Ir–Ru.

TABLE 1. SELECTED ELECTRON-MICROPROBE DATA ON Os-Ir-Ru-Pt ALLOYS

Analysis no.	4/97	4/76	5/120	7/33	7/37	7/44	6/114	3/13
				weight per cent				
Ru	2.55	43.93	18.24	12.93	13.05	15.75	10.22	11.96
Rh	0.22	1.81	0.97	2.32	2.36	3.04	1.82	4.07
Pd	nd	nd	nd	nd	nd	nd	nd	nd
Os	81.78	23.81	36.23	19.27	16.50	15.93	21.36	10.36
Ir	14.86	24.03	42.36	50.18	54.93	49.87	57.19	59.13
Pt	0.36	5.55	1.93	14.64	12.58	13.27	8.69	11.78
Fe	0.24	nd	nd	0.43	0.34	0.49	0.56	2.20
Cu	nd	nd	nd	nd	nd	nd	nd	nd
Ni	nd	nd	nd	nd	nd	0.27	nd	0.46
Total	100.01	99.13	99.73	99.77	99.76	98.62	99.84	99.96
				atomic proportions				
Ru	0.047	0.595	0.295	0.215	0.217	0.256	0.173	0.189
Rh	0.004	0.024	0.015	0.038	0.039	0.048	0.030	0.063
Pd	–	–	–	–	–	–	–	–
Os	0.795	0.171	0.312	0.170	0.146	0.137	0.193	0.087
Ir	0.143	0.171	0.361	0.438	0.480	0.426	0.510	0.490
Pt	0.003	0.039	0.016	0.126	0.108	0.112	0.076	0.096
Fe	0.008	–	–	0.013	0.010	0.014	0.017	0.063
Cu	–	–	–	–	–	–	–	–
Ni	–	–	–	–	–	0.007	–	0.012

nd: detected.
4/97 osmium, 4/76 ruthenium, 5/120 rutheniridosmine, 7/33, 7/37, 7/44 alloy in the miscibility gap, 6/114 iridium, 3/13 iridium in the Ir-Ru-Pt system

Pt–Fe alloy

Individual grains of Pt–Fe alloy are generally smaller than the Os–Ir–Ru alloy grains, ranging between 0.5 m and 1 mm in size; they are mostly well rounded, and show, in a few cases only, partly preserved crystal faces (Fig. 4f). Very common also is an intergrowth with grains of Os–Ir–Ru alloy (Fig. 4e). Grains of the Pt–Fe alloy are homogeneous, but variation is observed among grains. They invariably carry traces of Ru (<0.8 wt.%) and Os (<0.6 wt.%), but in isolated cases, low amounts of Pd (<0.4 wt.%). The content of Rh reaches up to 4.0 wt.%, whereas the Ir content varies between 0.3 and 9.0 wt.%. Besides Fe (6.8–10.8 wt.%), Cu (up to 2.2%) and Ni (up to 3.7%) are invariably present. Total (Fe,Cu,Ni) contents of the Pt–Fe alloy range from 25 to 35 at.%, with a peak at 30 at.% (Fig. 8); (Fe,Cu,Ni) contents are therefore much higher than the maxima at 16 or at 25 at.% observed at other localities worldwide (Cabri *et al.* 1996).

One 120 × 50 μm homogeneous tabular grain of Pt–Fe alloy with lamellae of osmium (Fig. 9a) contains 11.3 wt.% Fe, 5.8 wt.% Cu, and 4.3 wt.% Ni (Table 2, no. 15/23). This composition corresponds to 47.5 at.% (Fe,Cu,Ni) and could be tetraferroplatinum. According to the nomenclature of platinum–iron alloys (Cabri & Feather 1975), this identification is uncertain because the crystal structure would have to be determined by X-ray-diffraction (XRD). The grain also contains 2.4 wt.% Ir, 0.4% Rh, 0.3% Os, but no Ru and Pd. The contents of Ru, Rh, Pd, Os and Ir match well the composition of all other measured grains of Pt–Fe alloy.

Grains of Pt–Fe alloy are also often combined with the different variants of Os–Ir–Ru alloys. In some cases, drop-like inclusions of Ir occur in the Pt–Fe alloy near the boundary with osmium (Fig. 5f). Ir is generally the

TABLE 2. SELECTED ELECTRON-MICROPROBE DATA ON Pt-Fe ALLOY AND TULAMEENITE

Analysis no.	4/89	15/43	3/11	3/107	3/120	3/117	15/23	4/130
				weight per cent				
Ru	nd	nd	0.21	nd	nd	nd	nd	nd
Rh	0.31	3.34	2.75	2.55	1.83	0.75	0.37	0.20
Pd	0.42	0.21	nd	nd	nd	nd	nd	nd
Os	0.51	0.36	0.28	0.24	0.31	0.19	0.32	0.44
Ir	1.58	5.56	8.59	8.82	10.60	7.60	2.37	2.43
Pt	88.47	77.01	76.21	76.25	72.49	72.12	75.96	73.93
Fe	8.36	9.62	10.06	9.96	10.69	12.90	11.28	8.94
Cu	0.30	2.31	0.57	0.67	0.24	0.88	5.78	13.58
Ni	nd	1.99	1.47	1.44	3.67	6.24	4.34	0.50
Total	99.95	100.02	100.14	99.93	99.83	100.68	100.42	100.02
				atomic proportions				
Ru	-	-	0.003	-	-	-	-	-
Rh	0.005	0.046	0.039	0.037	0.025	0.019	0.009	0.010
Pd	0.006	0.003	-	-	-	-	-	-
Os	0.004	0.003	0.002	0.002	0.002	0.003	0.004	0.012
Ir	0.013	0.041	0.066	0.068	0.078	0.103	0.032	0.065
Pt	0.725	0.562	0.575	0.578	0.528	0.962	1.006	1.948
Fe	0.239	0.245	0.265	0.264	0.272	0.601	0.522	0.823
Cu	0.008	0.052	0.013	0.016	0.005	0.036	0.235	1.099
Ni	-	0.048	0.037	0.036	0.089	0.277	0.191	0.044

nd: not detected.

most abundant inclusion and commonly shows a crystallographic orientation relative to the host mineral (Fig. 5e). Osmium forms broad laths in grains of Pt–Fe alloy (Fig. 9a), whereas Ru occurs as fine parallel lamellae that show, in some cases, a clear crystallographic orientation (Figs. 6c, d).

Figure 6e is a back-scattered electron image of a rounded grain of osmium with a cap of Pt–Fe alloy. At higher magnification (Fig. 6f), fine lamellae aligned along crystallographic axes in the Pt–Fe alloy are observed. Electron-microprobe analyses gave the typical composition of Pt–Fe alloy, with 10.7 wt.% Fe, 0.2% Cu and 3.7% Ni, corresponding to an (Fe,Cu,Ni) content of 36.6 at.% for the matrix (Table 2, no. 3/120). The lamellae, however, contain 12.9 wt.% Fe, 0.9% Cu and 6.2% Ni, corresponding to 45.6 at.% (Fe,Cu,Ni)
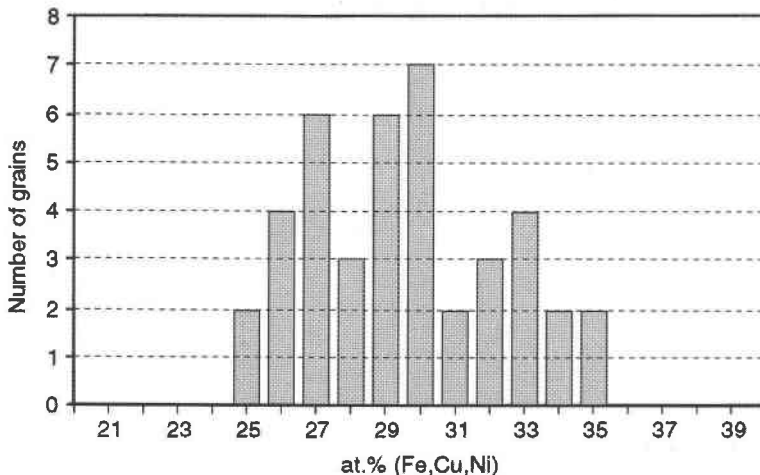

FIG. 8. Frequency plot showing the variation of (Fe,Cu,Ni) content of Pt–Fe alloy.

(Table 2, no. 3/117). This grain of alloy could be tetraferroplatinum. PGE concentrations differ only slightly, except for the Ir contents, which are 10.6 wt.% in the groundmass and 7.6 wt.% in the lamellae.

The lamellar inclusions of Pt–Fe alloy in rutheniridosmine (Fig. 5b), the euhedral or schlieren-like inclusions in ruthenium (Fig. 5d), as well as the blocky or drop-like inclusions in iridium (Fig. 5e) have the same composition as the single grains of Pt–Fe alloy or the grains that are intergrown with the Os–Ir–Ru alloys.

Tulameenite

Two irregular single grains of tulameenite 50 μm in diameter and narrow rims replacing Pt–Fe alloy were identified. Figure 9b shows an intergrowth between laths of osmium and Pt–Fe alloy where the latter is nearly completely replaced by tulameenite. Tulameenite always carries Ir (up to 2.4 wt.%), and traces (<0.5 wt.%) of Os and Rh (Table 2, no. 4/130). The compositions differ slightly among individual grains, the rims around the Pt–Fe alloy, and the grain of tulameenite
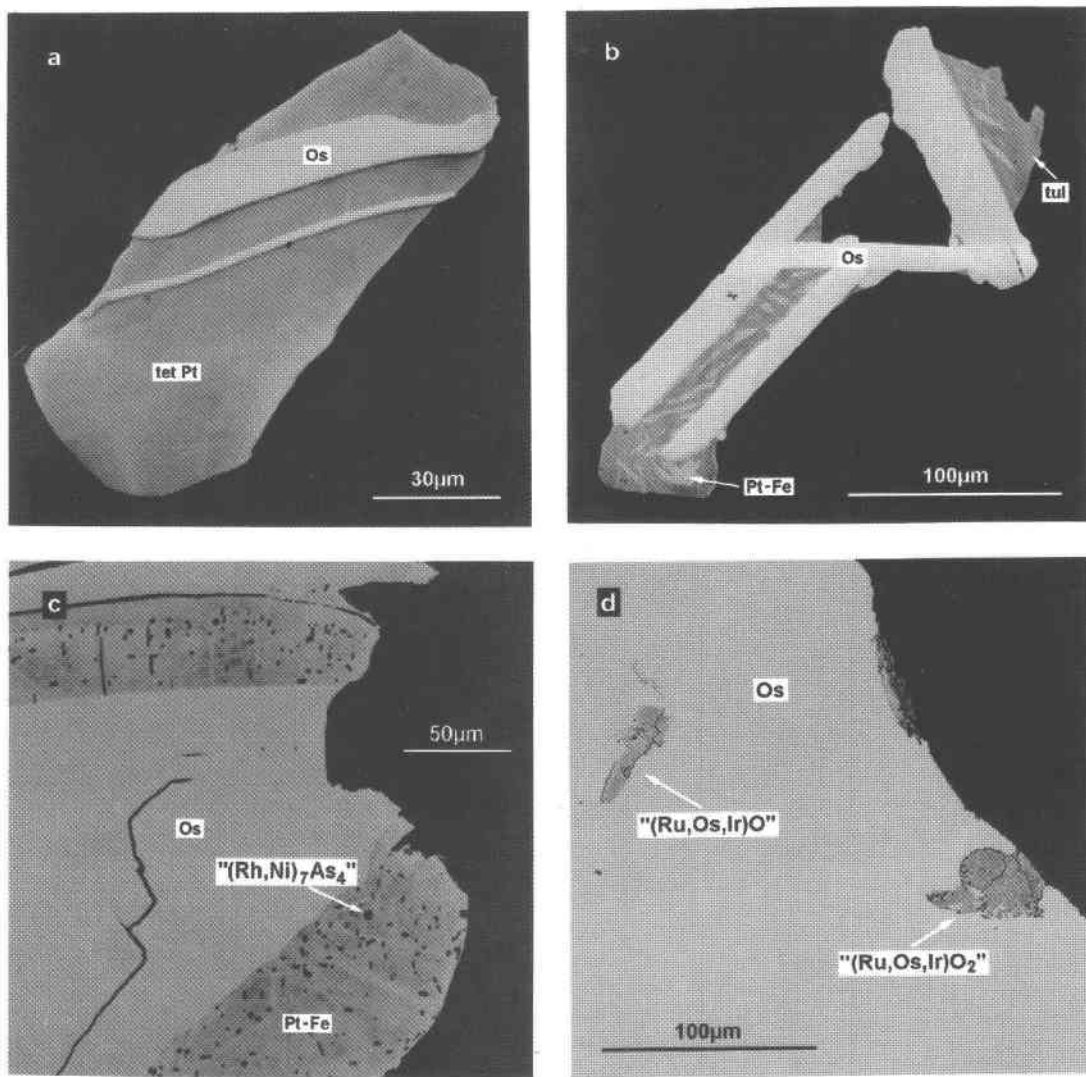

FIG. 9. Back-scattered electron images of various PGM. a. Grain of tetraferroplatinum? (tet Pt) with laths of osmium (Os). b. Composite grain of laths of osmium (Os) and Pt–Fe alloy (Pt–Fe) predominantly replaced by tulameenite (tul). c. Composite grain of osmium (Os) and Pt–Fe alloy (Pt–Fe) with tabular, partly oriented inclusions of undefined "(Rh,Ni)$_7$As$_4$". d. Undefined (Ru,Os,Ir) oxides as inclusions and at the boundary of osmium (Os).

intergrown with osmium. The total PGE content (2.05 at.%) is constant in the three different types of occurrences. The Fe + Ni content, however, increases from 0.85 at.% in the single grains to over 1.05 at.% in the marginal zones and up to 1.17 at.% in the tulameenite grain, whereas the content of Cu decreases in the same direction from 1.11 over 0.90 to 0.76 at.%.

Laurite

Laurite is the only PGE sulfide in the samples from the Aikora River area. It mainly occurs as irregular or drop-like inclusions near the margin of grains of the Os–Ir–Ru alloys, in some cases intergrown with or replacing irarsite; also, it fills cracks in the alloy grains or forms a narrow rim along them. In rarer instances, it forms euhedral inclusions up to 30 μm across in Pt–Fe alloy but not in the Os–Ir–Ru alloys. Electron-microprobe analyses show that in most grains, the content of Os varies between 1.4 and 39.3 at.%, and the Ir content, between 4.4 and 14.8 at.% (Fig. 10, Table 3). This composition corresponds to laurite and confirms the observation concerning the Ir content made on worldwide

TABLE 3. SELECTED ELECTRON-MICROPROBE DATA ON LAURITE

Analysis no.	3/155	4/150	5/52	6/95	9/5
			weight per cent		
Ru	51.89	52.11	56.47	32.58	21.65
Rh	0.41	4.01	0.89	0.27	0.22
Pd	nd	nd	nd	nd	nd
Os	1.41	nd	0.31	18.10	33.16
Ir	4.75	3.34	1.54	13.97	10.60
Pt	1.02	0.16	1.50	0.14	nd
S	34.44	34.11	37.19	29.14	27.89
As	3.47	3.43	nd	3.78	2.60
Total	97.39	97.16	97.90	97.98	96.12
			atomic proportions		
Ru	0.919	0.919	0.961	0.666	0.476
Rh	0.007	0.070	0.015	0.005	0.005
Pd	-	-	-	-	-
Os	0.013	-	0.003	0.197	0.387
Ir	0.044	0.031	0.014	0.150	0.122
Pt	0.009	0.001	0.013	0.001	-
S	1.924	1.897	1.995	1.877	1.932
As	0.083	0.082	-	0.104	0.077

nd: not detected.

occurrences by Cabri *et al.* (1996). It is conspicuous, however, that no erlichmanite is present in the samples. Laurite with a nearly stoichiometric composition in which Os is replaced by 1.5–6.8 at.% Rh occurs in a few grains of ruthenium (Table 3, no. 4/150). Similar observations on material from Yugoslavia were published by Krstić & Tarkian (1997).

PGE sulfarsenides

PGE sulfarsenides occur only as irregular inclusions near the margin of grains of Os–Ir–Ru alloys or Pt–Fe alloy, filling fractures or as a replacement-induced rim

TABLE 4. SELECTED ELECTRON-MICROPROBE DATA ON PGE SULFARSENIDES

Anal.	3/153	5/60	3/156	5/99	5/57	6/125	3/151	4/151
				weight percent				
Ru	0.99	5.17	1.97	10.88	3.77	0.33	14.01	34.04
Rh	0.49	11.69	0.76	0.70	36.96	4.44	2.35	14.22
Pd	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Os	n.d.	n.d.	9.16	22.73	n.d.	0.20	0.87	n.d.
Ir	57.76	32.63	48.60	28.87	5.88	24.88	13.64	8.78
Pt	3.69	10.20	4.31	1.40	5.67	30.06	27.04	0.26
As	26.69	27.37	25.44	15.19	33.72	34.16	28.93	13.64
S	9.95	11.93	9.67	18.70	14.30	5.79	11.99	26.03
Total	99.57	98.99	99.91	98.47	100.30	99.86	98.83	96.97
				atomic proportions				
Ru	0.029	0.136	0.059	0.274	0.083	0.010	0.366	0.666
Rh	0.014	0.303	0.022	0.017	0.797	0.134	0.060	0.274
Pd	-	-	-	-	-	-	-	-
Os	-	-	0.146	0.305	-	0.030	0.012	-
Ir	0.901	0.453	0.765	0.383	0.068	0.401	0.187	0.900
Pt	0.057	0.140	0.067	0.018	0.065	0.478	0.366	0.003
As	1.068	0.975	1.028	0.517	0.999	1.414	1.020	0.360
S	0.931	0.993	0.913	1.486	0.990	0.560	0.988	1.607

n.d.: not detected.
3/153 irarsite in the Ir–Pt–Ru system, 5/60 irarsite in the Ir–Rh–Pt system, 3/156 irarsite in the Ir–Os–Pt system, 5/99 irarsite in the Ir–Ru–Os system, 5/57 hollingworthite in the Rh–Ir–Ru system, 6/125 platarsite in the Pt–Ru–Ir system, 3/151 platarsite/ruarsite in the Pt–Ru–Ir system, 4/151 ruarsite in the Ru–Rh–Ir system.
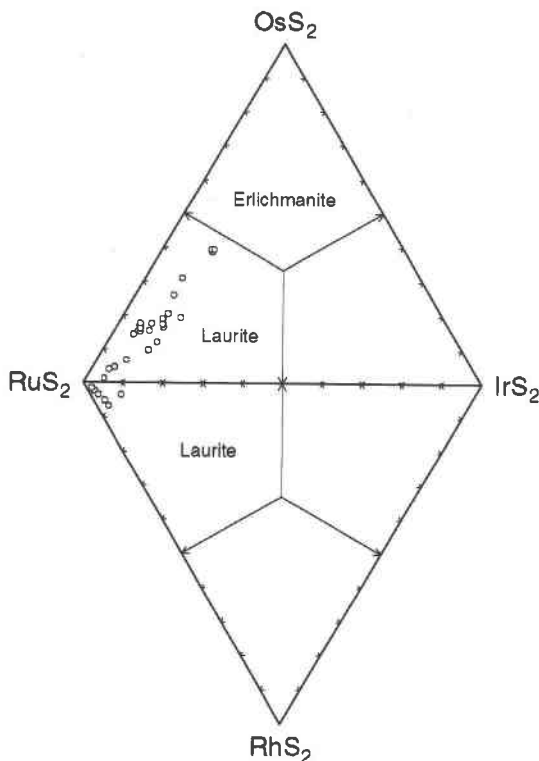

FIG. 10. The electron-microprobe-derived compositions of laurite in terms of the components RuS_2, OsS_2, IrS_2 and RhS_2.
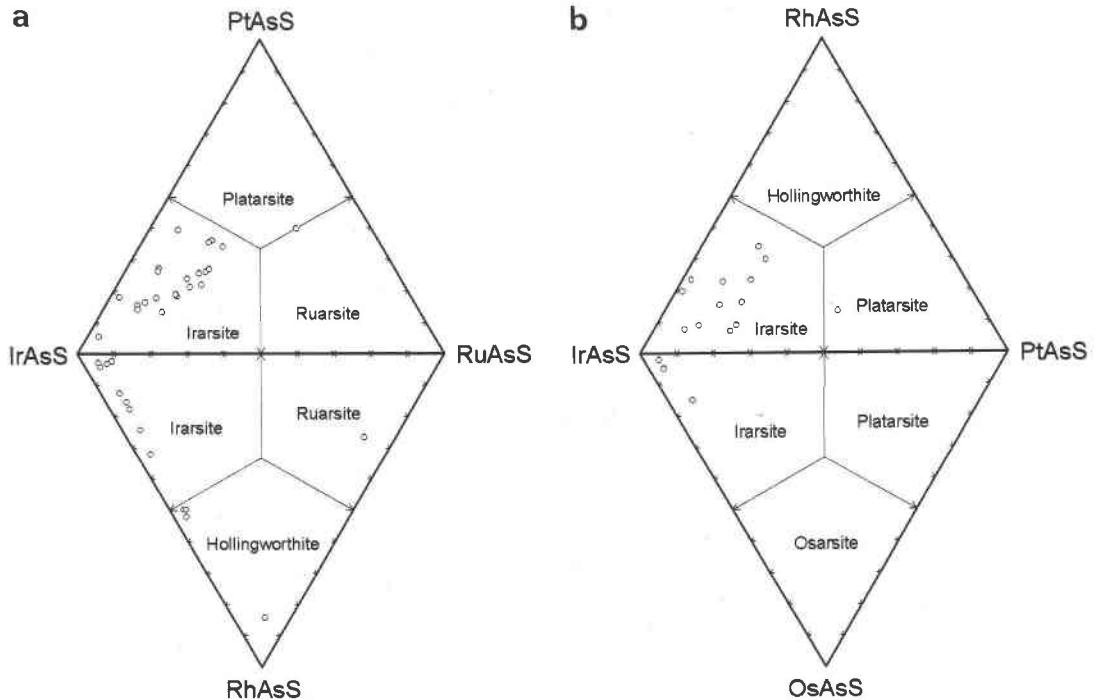
FIG. 11.   The electron-microprobe compositions of PGE sulfarsenides in terms of the components IrAsS–PtAsS–RuAsS–RhAsS (a) and IrAsS–RhAsS–PtAsS–OsAsS (b).

on them. Zoned crystals are very common. All PGE except Pd were found in the sulfarsenides, so that minerals in the systems IrAsS–PtAsS–RuAsS, IrAsS–RhAsS–RuAsS, IrAsS–RhAsS–PtAsS, IrAsS–OsAsS–PtAsS and IrAsS–RuAsS–OsAsS exist. Irarsite is by far the most common sulfarsenide (88%). It carries variable amounts, mainly of Pt and Rh and some Ru or Os (Table 4). Therefore, most compositions fall in the quaternary diagram IrAsS–PtAsS–RhAsS–RuAsS (Fig. 11a). The Pt content of irarsite varies between 5.7 and 39.5 at.%, the Rh content, between 2.3 and 32.0 at.%, and that of Ru, between 2.4 and 22.9 at.% in the system IrAsS–PtAsS–RuAsS, and between 3.8 and 8.3 at.% in the system IrAsS–RhAsS–RuAsS, respectively. Owing to the high Pt and Rh contents of irarsite, many compositions plot in the system IrAsS–RhAsS–PtAsS, and only few in the system IrAsS–OsAsS–PtAsS (Fig. 11b). The irarsite grains in these two plots contain between 1.7 and 21.8 at.% Pt, 7.0 and 33.8 at.% Rh, and 2.0 and 14.9 at.% Os. Only a few grains occur in which the content of Ru (8.7 to 28.5 at.%) and of Os (13.6 to 33.9 at.%) is higher than the content of Pt and Rh, whose compositions fall in the system IrAsS–RuAsS–OsAsS (Table 4, no. 5/99).

The remaining PGE sulfarsenides are hollingworthite (Table 4, no. 5/57), platarsite (Table 4, no. 6/125) and ruarsite (Table 4, no. 4/151). Analysis no. 3/151 gave a composition that falls right at the boundary between platarsite and ruarsite (Table 4). All these mineral grains are mostly intergrown with irarsite in rhythmically zoned crystals.

Sperrylite

Sperrylite occurs in two samples only. The irregular grains are up to 50 μm in size and surround grains of Os–Ir–Ru alloys or are intergrown with irarsite. Sperrylite carries up to 1 wt.% Ir, 2.9 wt.% Sb and traces of Ru, Rh, Os and S. The general formula is $(Pt_{0.96}Ir_{0.02}Rh_{0.01}Ru_{0.01})_{\Sigma1.00}(As_{1.90}Sb_{0.06}S_{0.04})_{\Sigma2.00}$.

Moncheite

Moncheite was identified as a small anhedral inclusion 25 μm across in Pt–Fe alloy. Besides traces of Os and Sb, an Ir content of 2.9 wt.%, and an Rh content of 9.2 wt.% are remarkable and corresponds to the formula $(Pt_{0.57}Rh_{0.37}Ir_{0.06})_{\Sigma1.00}(Te_{1.99}Sb_{0.01})_{\Sigma2.00}$. As far as we know, this is the highest content of Rh in moncheite ever reported.

Undefined Ir–Ni–Fe–Cu sulfide

One grain of osmium contains small triangular inclusions (<15 μm) and is attached to a 40 μm grain of

the same composition. The optical properties are similar to laurite. The mineral is a sulfide; it contains Ir as the main PGE, and traces of Rh and Pt besides Ni, Fe and Cu. The idealized calculated formula corresponds to $Ir(Ni,Fe,Cu)_2S_3$ (Table 5, no. 5/74).

Undefined Rh–Ni arsenides

The arsenide minerals ruthenarsenite and iridarsenite were first described from Papua New Guinea by Harris (1974), but were not found in our samples. However, two other PGE arsenides occur in the samples from the Aikora River area.

Large lamellae of Pt–Fe alloy intergrown with osmium contain many tabular, partly oriented inclusions up to 25 μm long (Fig. 9c). The small size of the grains did not allow determination of the optical properties. Electron-microprobe analyses show that the grains mainly consist of Rh (55.4 wt.%) and As (31.2 wt.%); they contain up to 2.3 wt% Ir, 4.1% Pt, 1.0% Pd, 0.2% Ru and 0.4% Sb, and also 6.7% Ni and 0.7% Fe (Table 5, no. 5/79). The formula was calculated as $(Rh_{5.24}Pt_{0.20}Ir_{0.12}Pd_{0.09}Ru_{0.02}Ni_{1.11}Fe_{0.12})_{\Sigma6.90}$ $(As_{4.06}Sb_{0.03})_{\Sigma4.09}$ or $(Rh,Ni)_7As_4$.

Other grains of Pt–Fe alloy contain very small (<10 μm) needles, which are dark in back-scattered images (BEI). An exact analysis of these needles was not possible because of their small size. The main elements are Rh (58.6 wt.%) and As (31.0 wt.%). The other elements amount to 0.2% Ru, 1.2% Pd, 0.4% Ir, 4.4% Pt, 0.4% Fe, 0.4% Cu, 4.2% Ni and 0.3% Sb. The Pt, Ir, Fe and Cu reported here could be due to contamination from the host mineral, the Pt–Fe alloy. On the other hand, the contents of Ru and, above all, Pd are significantly higher, and Os is absent in the needles, in contrast to the surrounding mineral phase. The Ni content (4.2 wt.%) of the inclusions also is higher than in the host mineral (1.2 wt.%). The following formula can thus be proposed: $(Rh_{1.54}\ Pt_{0.06}Pd_{0.03}Ni_{0.19}Fe_{0.02}Cu_{0.02})_{\Sigma1.86}$ $(As_{1.12}Sb_{0.01})_{\Sigma1.13}$ or, ideally, $(Rh,Ni)_2As$ (Table 5, no. 10/48).

A similar phase but with a higher content of Ni was described by Hagen *et al.* (1990) from PGM placer deposits in Burma and by Corrivaux & Laflamme (1990) from the Thetford Mines area, Quebec.

In conclusion, rhodium arsenides possibly also occur in the samples from Papua New Guinea besides the Ru and Ir arsenides described by Harris (1974). It is remarkable that both undefined phases contain up to 1.2 wt.% Pd, whereas all other analyzed PGM from the Aikora River area are nearly free of Pd.

Undefined Ru–Os–Ir oxide

The existence of natural PGE oxides has been a subject of controversy for a long time. The possibility of measuring the concentration of light elements increased with the development of a new type of analyzing crystals for the electron microprobe. Cabri *et al.* (1981)

TABLE 5. ELECTRON-MICROPROBE DATA ON UNDEFINED PGE SULFIDES, ARSENIDES AND ?OXIDES

Analysis no.	5/74	5/79	10/48	6/149	6/153
			weight per cent		
Ru	nd	0.23	0.16	29.47	16.72
Rh	1.06	55.36	58.58	nd	0.25
Pd	nd	1.01	1.21	nd	nd
Os	nd	nd	0.35	34.01	27.81
Ir	45.18	2.30	0.35	23.76	26.94
Pt	1.20	4.10	4.39	0.81	6.13
Fe	8.78	0.70	0.43	3.29	4.45
Cu	5.84	nd	0.41	nd	nd
Ni	13.18	6.71	4.18	0.39	0.45
S	23.59	nd	nd	nd	nd
As	nd	31.22	30.96	nd	nd
Sb	nd	nd	0.26	nd	nd
O*	-	*	-	8.27	17.25
Total	98.83	101.63	100.93	100.00	100.00
			atomic proportions		
Ru	-	0.023	0.004	0.494	0.300
Rh	0.042	5.254	1.542	-	0.004
Pd	-	0.093	0.031	-	-
Os	0.996	-	-	0.303	0.266
Ir	0.025	0.117	0.005	0.209	0.255
Pt	0.646	0.205	0.061	0.007	0.057
Fe	0.378	0.123	0.021	0.100	0.155
Cu	0.922	-	0.017	-	-
Ni	3.021	1.116	0.193	0.011	0.014
S	-	-	-	-	-
As	-	4.069	1.120	-	-
Sb	-	-	0.006	-	-
O	-	-	-	0.876	1.959

* calculated by difference; nd: not detected.
5/74 Ir–Ni–Fe–Cu sulfide, $Ir(Ni,Fe,Cu)_2S_3$?, 5/79 Rh–Ni arsenide, $(Rh,Ni)_7As_4$?, 10/48 Rh–Ni arsenide, $(Rh,Ni)_2As$?, 6/149 Ru–Os–Ir oxide, (Ru,Os,Ir) ?, 6/153 Ru–Os–Ir oxide, $(Ru,Os,Ir)O_2$?

assumed the occurrence of Pt oxide in samples from Ethiopia, as did Nixon *et al.* (1990) in material from Tulameen, British Columbia. However, the first quantitative electron-microprobe analyses of PGE oxides were carried out by Weiser (1991) on samples from Burma and Colombia. In the meantime, PGE oxides were reported from numerous different localities around the world (*e.g.,* Augé & Legendre 1994, Jedwab 1995, Cabri *et al.* 1996, Garuti *et al.* 1997, Krstić & Tarkian 1997).

One grain of osmium from the Aikora area contains an unknown mineral in fractures and at the grain boundary (Fig. 9d). The phase looks grey with a brownish tinge, is weakly anisotropic, and shows undulatory extinction under reflected light in oil immersion. Electron-microprobe analyses gave the composition of an Ru–Os–Ir mineral with a low sum: 91.73 and 82.75 wt.%. A wavelength-dispersion scan in both grains clearly showed the presence of oxygen. The calculated formula corresponds to $(Ru,Os,Ir)O$ (Table 5, no. 6/149) for the grain within the Os–Ir–Ru alloy, and $(Ru,Os,Ir)O_2$ (Table 5, no. 6/153) for the grain at the boundary of the alloy. Garuti *et al.* (1997) described a similar, but much more Fe-rich phase as inclusions in chromitites from Urals, whereas Krstić & Tarkian (1997) found nearly pure Ru oxide in placers from the Veluće ophiolite complex, Yugoslavia.

DISCUSSION AND CONCLUSIONS

The PGM concentrates from the Aikora River area consist almost exclusively of grains of Os–Ir–Ru alloys

and Pt–Fe alloy as primary phases. The other observed minerals, sulfides, arsenides, sulfarsenides, tellurides and undefined phases of platinum-group elements, are rare and either occur as inclusions or, more commonly, as alteration products in fractures or as a rim on the alloys. This relatively monotonous composition is somewhat in contrast to other PGM placer deposits, *e.g.*, from British Columbia (Raicevic & Cabri 1976, Nixon *et al.* 1990), Burma (Hagen *et al.* 1990), Colombia (Cabri *et al.* 1996) or the Urals, Russia (Cabri *et al.* 1996), which show a far more varied array of minerals.

Most single grains in the system Os–Ir–Ru show only limited variation in their compositions. They mostly plot close to the "triple point" of the triangular diagram, overlapping the boundary between osmium and rutheniridosmine. The coexistence of various minerals of the system Os–Ir–Ru and their crystallographically oriented intergrowth in many composite grains prove a high-temperature origin. The compositions of inclusions of osmium, ruthenium or iridium in the different types of Os–Ir–Ru alloy or in Pt–Fe alloy are similar to the compositions of the single grains. This statement applies both for the major and trace elements. Whereas Pd is absent in both single grains and in inclusions of Os–Ir–Ru alloys, Rh and Pt are invariably present in both types in the same proportions. This finding contrasts with observations of Krstić & Tarkian (1997), who found higher contents of Pt in Os–Ir–Ru alloys coexisting with Pt–Fe alloy than in single grains. All compositions that plot in the miscibility gap of the system Os–Ir–Ru are characterized by high contents of platinum. These grains probably crystallized at higher temperatures.

No significant differences were observed between the compositions of discrete grains and inclusions of Pt–Fe alloy in Os–Ir–Ru alloys. They all carry traces of Rh, Ru and Os and contain significant amounts of Ir. The total (Fe,Cu,Ni) contents lie between 25 and 35 at.%, with the peak of the frequency at 30 at.% for both habits of Pt–Fe alloy. The higher maxima compared with other PGM placer deposits worldwide (Cabri *et al.* 1996) probably implies higher contents of Fe, Cu and Ni in the primary ore-forming system.

Composite grains of Os–Ir–Ru alloys and Pt–Fe alloy are very common, as is a lamellar or symplectitic intergrowth between the two phases, drop-like inclusions in one another, or polycrystalline aggregates of the two types of alloys. Exsolution lamellae of tetraferroplatinum or ruthenium in Pt–Fe alloy also were observed. All these features are consistent with a high temperature of formation.

It is remarkable that there is a nearly complete absence of sulfides. Rare Rh-enriched and Os-depleted laurite occurs as primary inclusions in the alloys. The tabular or needle-like inclusions of undefined Rh–Ni arsenides and their orientation in Pt–Fe alloy suggest a magmatic stage of formation. On the other hand, the greatest part of laurite, arsenides, sulfarsenides and probably PGE oxides mainly occur as alteration products in fractures or as a rim on the alloys.

The composition of the grains of Os–Ir–Ru alloys and the Pt–Fe alloy in the single grains and in the inclusions, as well as the features of intergrowth and the scarcity of sulfides, indicate a complex Os–Ir–Ru–Rh–Pt–Fe solid-solution system depleted in sulfur, from which the different alloys crystallized at high temperature.

The dominance of Os–Ir–Ru alloys and other Ru-bearing PGM is described from ophiolite complexes worldwide, *e.g.*, Cyprus (Constantinides *et al.* 1980), Oregon (Stockman & Hlava 1984) or Shetland (Tarkian & Prichard 1987), and from placer deposits related to ophiolites, *e.g.*, in Tasmania (Ford 1981) and Burma (Hagen *et al.* 1990). The similarity in the mineral assemblages described leads to the inference that the PGM of the placer deposits of the Aikora River area originate from primary deposits in the ophiolites of the Papuan Ultramafic Belt, whose nature and location are still unknown.

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