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PLATINUM-IRON ALLOYS: A NOMENCLATURE BASED ON A STUDY OF NATURAL AND SYNTHETIC ALLOYS*

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ABSTRACT

A new nomenclature is proposed for Pt-Fe alloys. The nomenclature is based on a study of the synthetic Pt-PtFe system and on natural samples from the Tulameen and Similkameen rivers, British Columbia, from Witwatersrand gold mines located in the Transvaal and the Orange Free State, from the Stillwater Complex, Montana, and from the old Mooihoek platinum deposit, Transvaal.

The proposals take into account minor amounts of Ir, Pd, Rh, Os, Ru that often substitute for Pt and also minor amounts of Cu, Ni, Sb that substitute for Fe.

a) *Native platinum* is defined as a face-centered cubic alloy with Pt$\geq$80 at.%.

b) *Ferroan platinum* is defined as a variety of native platinum (Pt,Fe), with a face-centered cubic structure and with Fe between 20 and 50 at.%.

c) *Isoferroplatinum* is defined as a new species with a primitive cubic structure, and a composition usually near Pt_3Fe, but with no definite compositional limits.

d) *Tetraferroplatinum* is redefined as a distinct species with tetragonal symmetry and a composition near PtFe, but for which the compositional limits are not known exactly.

e) If only compositional data are known, the mineral is referred to by the general name *platinum-iron alloy* or *Pt-Fe alloy*.

f) The terms "polyxene", "ferroplatinum", "tetragonal ferroplatinum", and "iron-bearing platinum" should no longer be used.

INTRODUCTION

Native platinum was first known to occur in South America in the sixteenth century and was brought to Europe by the surveyor Don Antonio de Ulloa y Gracia de la Torre (Wagner 1929). He referred to the metal as *Platino del pinto* in a narrative, published in 1748. Studies of grains of the metal soon established that it was alloyed with several elements, of which a common one was iron. A nomenclature evolved over the years which was principally based on the iron-content of the platinum. Unfortunately, names had been applied to grains analyzed by bulk assay and prior to the discovery and application of *x*-ray diffraction to define minerals. Native platinum has also never been defined quantitatively. Haüy (1801), under the heading "platine", described as a unique species "platine natif ferrifère" which may be translated as iron-bearing native platinum. With time, the terms "polyxene" and "ferroplatinum" were generally applied to low-Fe and high-Fe alloys, respectively, but without any consistency, as is evident in Table 1. The detailed discussion of such native alloys by Razin (1970) is likewise difficult to apply to any nomenclature because his observations were made on grains which had either been assayed or analysed qualitatively by spectroscopy. He defined "polyxene" as having 2.5-12.1% Fe but subdivided it further into "low-iron polyxene" (2.5-5.6% Fe) and "high-iron polyxene" (9.9-12.1% Fe). The latter apparently could be of either cubic or tetragonal symmetry. He also defined "ferroplatinum" as having 15.5-28.1% Fe and subdivided it further into "low-iron ferroplatinum" with 15.5-19% Fe and "high-iron ferroplatinum" with 25.3-28.1% Fe. The former was reported as having either cubic or tetragonal symmetry. Razin *et al.* (1973, p. 102) introduced the term "iron monoplatinide" which they refer to as "ferroplatinum" with $(Fe,Ni,Cu)_{1+x}Pt$ composition in Table 3 and as "tetragonal ferroplatinum" in Table 8. Cabri (1972) suggested that the nomenclature of Pt-Fe alloys needed further refinements and that there may be some new species requiring definition.

A new nomenclature, which has been approved by the Commission on New Minerals and Mineral Names, I.M.A., is proposed for platinum and platinum-iron alloys. This nomenclature supports the observations of earlier workers and also presents new *x*-ray and phase equilibrium data essential to understanding these alloys.

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TABLE 1. EXAMPLES OF TERMINOLOGY APPLIED TO PLATINUM AND Pt-Fe ALLOYS.

	Name Used	Brief Description	Reference
PLATINUM	Gediegen Platin	Essentially Pt	Hausmann (1813) p. 98
	Hexaedrisches Platin (Gediegen Platin)	Native Pt, not magnetic	Breithaupt (1832) p. 256-257.
	Reine Platin	Pure Pt and Pt-Pd	Duparc in Doetler & Leitmeier (1926) p. 980
	native platinum	Pt variable, 1-10% Fe, other elements	Genkin (1968) p. 12
	platinum	4 (Pt) *syn.* Polyxen *var.* ferroplatinum	Hey (1962) p. 6
POLYXENE	Polyxen	Platinum with some Fe	Haussman (1813) p. 97
	Polyxen	80-88% Pt, 6-10% Fe, non-magnetic	Duparc in Doetler & Leitmeier (1926) p. 980
	polyxene	80-90% Pt, 6-11% Fe	Vysotzki (1928) in Wagner (1929) p. 11
	var. polyxene	80-90% Pt, 3-11% Fe, non or slightly magnetic	Dana (1944) p. 107
	Polyxen	Pt with 0.5 - 12% Fe, isotropic	Yushko-Zakharova *et al.* (1970) p. 788
FERROPLATINUM	Eisen-platin (Siderisches Platin)	Iron-platinum, magnetic	Breithaupt (1832) p. 119
	iron-platinum	73.58 - 83.07% Pt, 10.79 - 12.98% Fe (Pt_2Fe)	Dana (1854) p. 13
	Ferro-platin	70-78% Pt, 12-20% Fe	Duparc in Doetler & Leitmeier (1926) p. 980
	ferroplatinum	71-78% Pt, 16-20% Fe	Vysotski (1928) in Wagner (1929) p. 11
	var. ferrian platinum	Pt with up to 28% Fe, magnetic	Dana (1944) p. 107
	ferroplatinum	71-81% Pt, 11-13% Fe, magnetic	Maslenitskii (1948) in Genkin (1968) p. 12
	ferroplatinum	a = 3.867, c = 3.735 A	Mikheev *et al.* (1961) in Genkin & Basova (1965) p. 214
	tetragonal ferroplatinum	(Pt,Pd)Fe, a = 3.84, c = 3.78 A	Genkin & Basova (1965) p. 214
	ferroplatinum	Pt_2Fe - Pt_3Fe (i.e. 8.7 - 12.5% Fe), cubic	Genkin (1968) p. 15
	ferroplatinum	Pt with 12-27% Fe, slightly anisotropic	Yushko-Zakharova *et al.* (1970) p. 788
	ferroplatinum	$Pt_{10}Fe_7NiCu$ - $Fe_7Pt_6Ni_{1.5}Cu$ (i.e. to 22.87% Fe, 8.8% Ni + Cu), cubic	Razin *et al.* (1973) p. 119
	tetragonal ferroplatinum	$PtFe_{1+x}$, tetragonal	Razin *et al.* (1973) p. 119

SAMPLES AND PROCEDURES

Samples from placer and primary deposits, as well as synthetic platinum-iron alloys, were examined in this study. The localities of the natural samples are listed in the tables. The samples were studied by ore microscopy, x-ray diffraction analysis, and electron probe microanalysis. The platinum alloys from the Witwatersrand mines were studied in the Anglo American Research Laboratories (AARL), Crown Mines, whereas those from British Columbia and Mooihoek, Transvaal, were studied in the Mines Branch Laboratories (MBL), Ottawa. Some additional x-ray diffraction analyses on Witwatersrand samples were also performed at MBL as were all the syntheses.

Compositions were determined at the MBL with a Materials Analysis Company model 400 electron probe microanalyser using, as standards, iridium, palladium, and nickel metals and synthetic PtFe, Pt_3Fe, $PtSb_2$ and PtCu. Corrections were applied using edition VII of the program by Rucklidge & Gasparrini (1969). At the AARL, compositions were determined with a Jeol JXA-5A electron probe using, as standards, iridium, osmium, ruthenium, nickel, rhodium, and copper metals and synthetic Pt_3Fe. Corrections were applied using the correction program of Duncumb & Jones (1969).

THE PT-PTFE SYSTEM

The Pt-Fe binary phase diagram presented in the review by Hansen & Anderko (1958) shows evidence of broad order-disorder transformations in the regions of the compositions $PtFe_3$, PtFe and Pt_3Fe. There are also some magnetic transformations, but none of these is well-defined, especially in the region near Pt_3Fe. Synthetic ordered Pt_3Fe is antiferromagnetic, but cold-working disorders the structure, producing strong ferromagnetism (Crangle 1959). Synthetic ordered PtFe is known to be ferromagnetic (Westbrook 1967, p. 541).

At high temperatures a continuous disordered (face-centered cubic) solid solution exists between Pt and Fe (shown as γ in Hansen & Anderko's Fig. 387). The face-centered cubic symmetry of these alloys is not affected by the relative concentrations of the two constituents (Pt and Fe) because the two sets of sites are randomly occupied. In the case of Pt_3Fe, for example, when disorder is complete, the odds of a given site being occupied by a Pt atom are 3:4 and the odds of finding a site occupied by an Fe atom are 1:4. On cooling, or below the critical temperature before disorder is complete, the atoms are packed in a regular manner resulting in a primitive cubic (Fig. 1b) rather than a face-centered cubic cell (Fig. 1a). The stoichiometry, Pt_3Fe, arises because each of the six open circles (Pt in Fig. 1b) is shared between two adjacent unit-cells, therefore representing three platinum atoms, whereas the eight solid circles (Fe) are each shared between eight contiguous unit-cells and, therefore, jointly represent one iron atom.

If the Pt atoms in the top and bottom faces of the cell in Figure 1b are replaced by Fe atoms, then the stoichiometry becomes PtFe and a layered lattice results. Because of the layering, the lattice no longer has cubic symmetry but is now tetragonal. When this ordered array is heated, the layering is lost through randomization until, in the completely disordered state, a cubic structure identical with that of Pt_3Fe (Fig. 1a) is obtained. The only difference between the two is that now there is an equal probability of finding a Pt or an Fe atom in any site.

Ordered phases having specific stoichiometries and distinct structures within a disordered alloy solid-solution have been recognized by metallurgists and are referred to as Kurnakov compounds (*cf.* Cu_3Au and CuAu). A good description of this terminology is given by Kornilov (1967).

A series of ten compositions in the Pt-PtFe partial binary system was synthesized originally at 1200°C. by the technique described by Cabri *et al.* (1973). The results of this study are shown in Figure 2. Because no high-temperature *x*-ray diffraction studies were made it is not known whether the alloys with compositions near Pt_3Fe have the primitive cubic structure at 1200°C, or whether the disordered face-centered cubic structure is unquenchable. Hansen & Anderko (1958) report that several investigators have stated that the γ-phase (face-centered cubic) at the PtFe composition cannot be quenched, whereas Kussman & Rittberg (1950) report that it can. The partial phase diagram and order and disorder in the natural Pt-Fe alloys are discussed in more detail below.

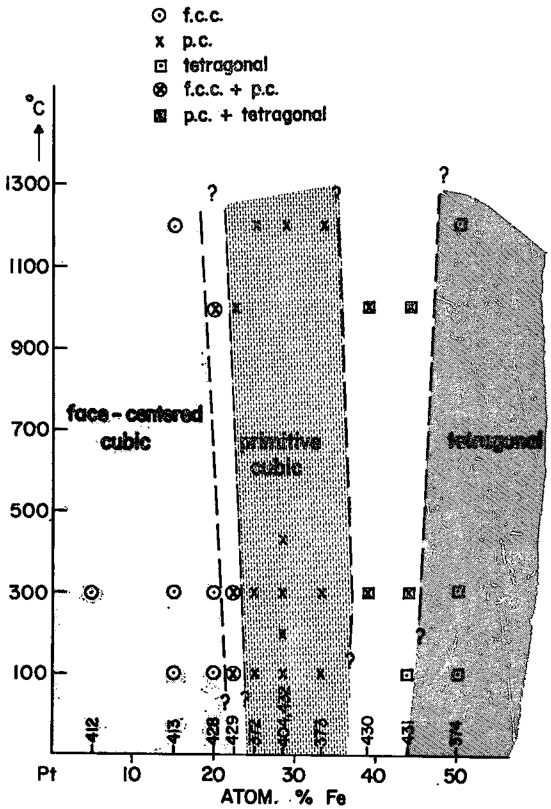


FIG. 2. Experimental results along the partial Pt-PtFe binary composition diagram. The vertical numbers along the abscissa represent run numbers. Interpretations based on *x*-ray powder diffraction at room temperature with Debye-Scherrer cameras of samples previously synthesized at 1200°C, then annealed at the temperatures indicated. The samples were ground prior to annealing to avoid any cold-working during samnle preparation.

Linear plots of cell-edges versus Fe atomic per cent are given in Figure 3. In order to show the relationship, if any, of the tetragonal compounds, the volumes versus atom per cent Fe are plotted in Figure 4. The cell edges and volumes used in these diagrams were obtained from measurements of Debye-Scherrer films from samples annealed at 300°C and then quenched. The line of best fit for the face-centered cubic samples was calculated to be $a = 3.9224 - 0.0024 \times$ (at.% Fe) from the following data points: 100% Pt, 3.9231 Å; 95 at.% Pt, 3.910 Å; 85 at.% Pt, 3.890 Å; 80 at.% Pt, 3.877 Å; and 77.5 at.% Pt, 3.872 Å. The line of best fit for the primitive cubic samples was calculated to be $a = 3.90077 - 0.00141 \times$ (at.% Fe) from the following data points: 75 at.% Pt, 3.866 Å; 71.42 at.% Pt, 3.860 Å; 66.64 at.% Pt, 3.853 Å; and 60.92 at.% Pt, 3.846 Å. The same data were used to calculate the unit-cell volumes and the lines of best fit which are $V(f.c.c.) = 60.3469 - 0.10222 \times$ (at.% Fe) and $V(p.c.) = 59.3341 - 0.06312 \times$ (at.% Fe). The *x*-ray powder patterns for some of these samples are tabulated in Table 5.

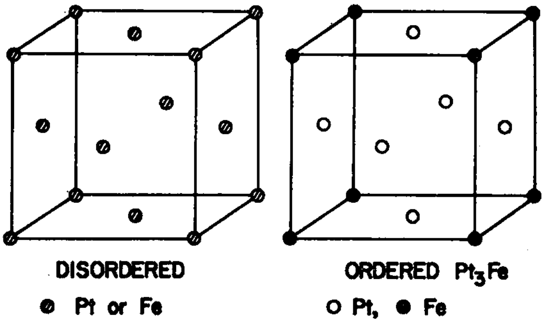


FIG. 1. a. Disordered Pt_3Fe (face-centered cubic), and b. ordered Pt_3Fe (primitive cubic).

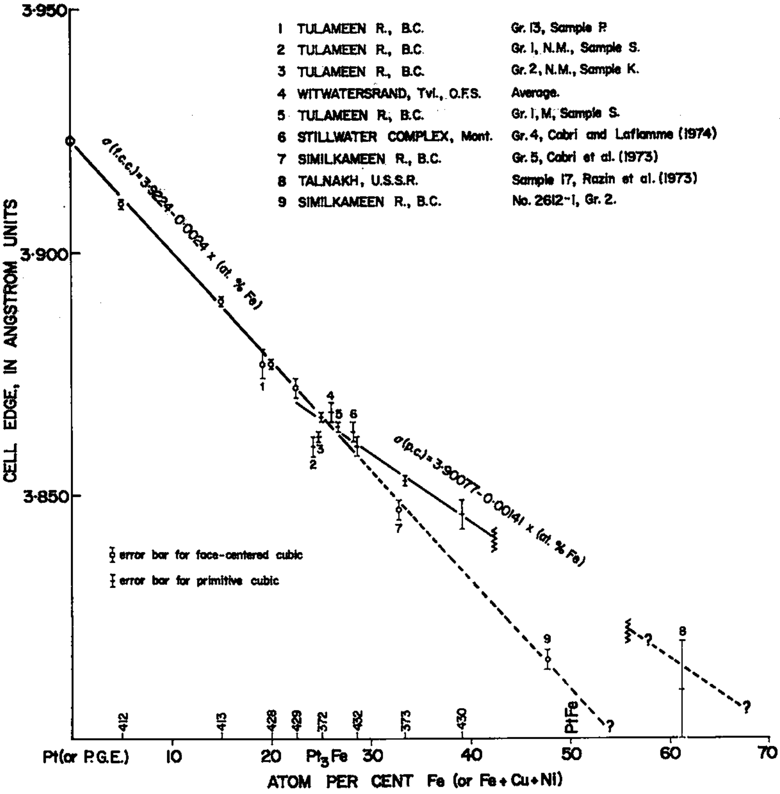


FIG. 3. Cell edge versus atom per cent Fe (+Cu+Ni) for Pt-Fe alloys. Minor quantities of Ir, Rh, Os, Ru or Pd, if present, are calculated as Pt for the natural alloys. Sample 4 (Witwatersrand) is the average of 55 grains from mines in the Transvaal and the Orange Free State. The average unit cell of $a = 3.869$Å for that sample was obtained from nine grains.

NATURAL PLATINUM-IRON ALLOYS

Platinum-iron alloys from diverse geological environments and ages were studied and some data were selected from the literature. The platinum-group minerals occurring in placers in the areas of the Tulameen and Similkameen rivers were considered by Cabri (1974), in agreement with earlier studies of the area, to have been derived from weathered portions of the Late Triassic Tulameen zoned ultramafic complex. The mineralogy of some of the thirteen platinum-group minerals found in the placers are described by Cabri *et al.* (1973) and Cabri & Hey (1974).

Platinum-iron minerals from the Precambrian stratiform Stillwater Complex (Cabri & Laflamme 1974) are considered to be primary minerals crystallized *in situ.*

Platinum-iron alloys from the Precambrian Witwatersrand gold-uranium conglomerates (reefs) were derived from ten mines in the Transvaal and the Orange Free State. The alloys represent but one of about twenty platinum-group minerals found in the Witwatersrand reefs by Feather (1975), who also discusses earlier papers and the origin of these minerals in the Witwatersrand. The platinum-iron alloys commonly occur mainly as irregular exsolution laths in osmiridium and iridium (Fig. 5), and sometimes form distinct intergrowths with other platinum-group minerals (Fig. 6). Rare free grains are relatively smaller than the average platinum-group mineral grain (*i.e.* less than about 80 μm), and commonly contain minute inclusions of other platinum-group minerals such as moncheite, michenerite (Fig. 7), Pt-Rh alloy, and a rhodium sulphide.

The platinum-iron alloys from the old Mooihoek mine No. 147 (Transvaal) occurred in a hortonolite dunite sample (No. L 820). The pla-

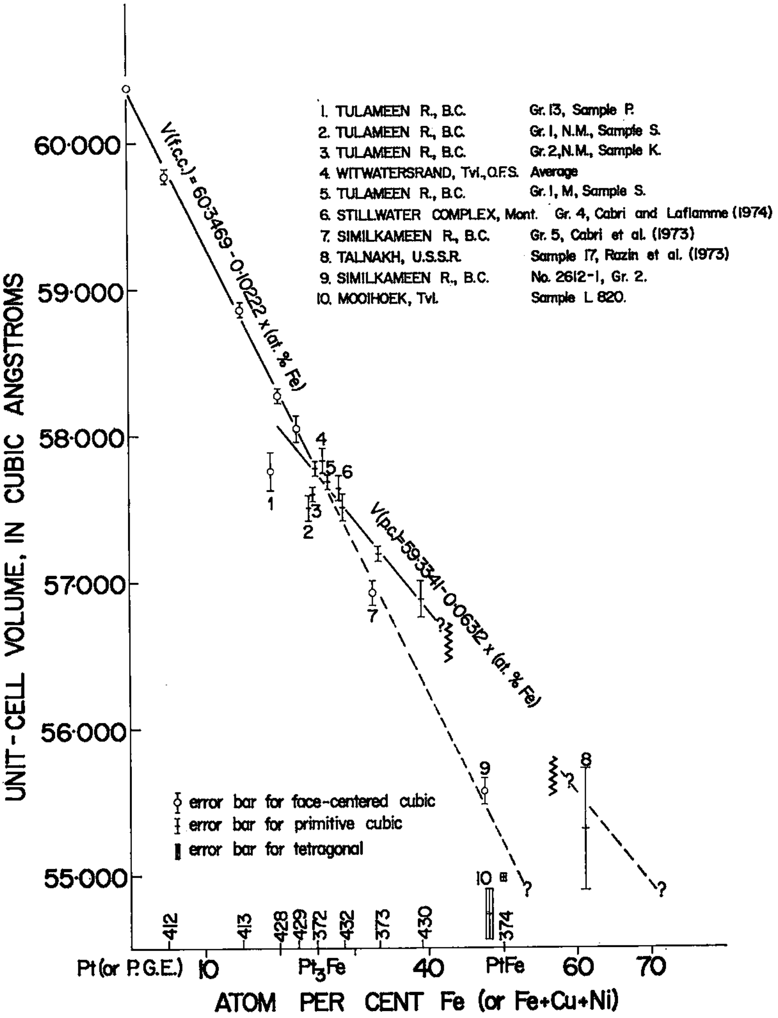


FIG. 4. Unit-cell volume versus atom per cent Fe(+Cu+Ni) for Pt-Fe alloys.

tinum-iron alloys consist of core areas with a Pt:Fe ratio of approximately 2:1 and rim areas where the ratio is closer to 1:1. The alloys also contain inclusions of geversite ($PtSb_2$), irarsite (IrAsS), and antimonian sperrylite, as determined by qualitative energy dispersive probe analyses.

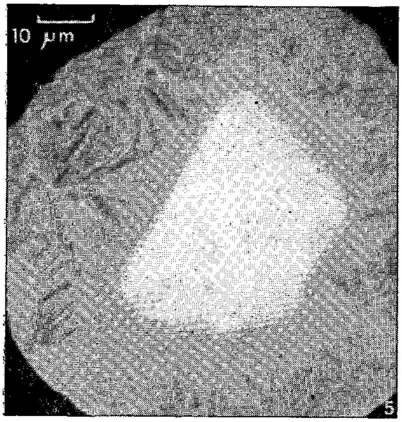
NATURAL PLATINUM-IRON ALLOYS: COMPOSITIONAL AND X-RAY DIFFRACTION CHARACTERISTICS

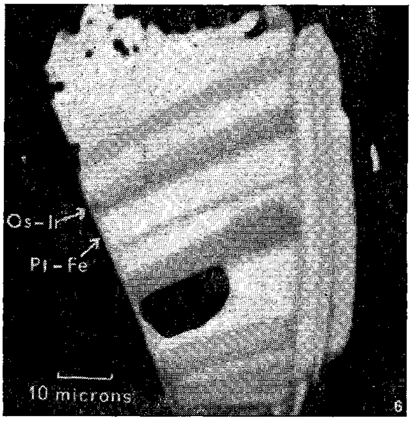
Electron probe analyses (Tables 2 & 3) of natural platinum-iron alloys from a variety of

TABLE 2. ELECTRON PROBE ANALYSES OF NATURAL PLATINUM-IRON ALLOYS

Sample No.	Locality	Weight Per Cent								Atomic Proportions .									
		Pt	Ir	Pd	Fe	Cu	Ni	Sb	Total	Pt	Ir	Pd	Σ	Fe	Cu	Ni	Sb	Σ	Name
1	Tulameen R.	91.3	0.25	0.54	5.4	1.0	0.06	n.d.	98.55	3.19	0.01	0.03	*3.23*	0.65	0.11	0.01	---	*0.77*	*native platinum*
2	Tulameen R.	89.7	0.18	---	6.2	2.2	n.d.	n.d.	98.28	3.03	0.01	---	*3.04*	0.73	0.23	---	---	*0.96*	*isoferroplatinum*
3	Tulameen R.	90.2	n.d.	---	7.6	0.94	0.06	n.d.	98.8	3.01	---	---	*3.01*	0.88	0.10	0.01	---	*0.99*	*isoferroplatinum*
5	Tulameen R.	88.9	0.05	---	8.8	0.21	0.06	0.60	98.62	2.93	---	---	*2.93*	1.01	0.02	0.01	0.03	*1.07*	*isoferroplatinum*
6	Stillwater* Complex	88.4	n.d.	---	9.6	0.2	0.1	n.d.	98.3	2.87	---	---	*2.87*	1.10	0.02	0.01	---	*1.13*	*isoferroplatinum*
7	Similkameen R.	84.8 (83.8-85.8)	2.2	---	10.8 (10.6-11.1)	1.5	n.d.	n.d.	99.3	2.62	0.07	---	*2.69*	1.17	0.14	---	---	*1.31*	*ferroan platinum*
8	Talnakh**	68.5	---	---	22.8	3.6	5.2	---	100.1	1.55	---	---	*1.55*	1.81	0.25	0.39	---	*2.45*	*???*
9	Similkameen R.	74.8	3.6	---	18.5 (17.7-18.7)	1.6 (1.5-1.9)	0.33	n.d.	98.83†	2.00	0.10	---	*2.10*	1.73	0.14	0.03	---	*1.90*	*ferroan platinum*
10	Mooihoek (rim)	78.0 (77.2-77.8)	0.32 (0.05-0.74)	---	14.9 (13.8-16.1)	6.1 (5.2-7.2)	0.50 (0.44-0.61)	0.40 (.14-.61)	100.22	2.06	0.01	---	*2.07*	1.38	0.49	0.05	0.01	*1.93*	*tetraferroplatinum*
11	Mooihoek (core)	86.7	0.57	---	10.9	0.84	0.34	0.43	99.78	2.67	0.02	---	*2.69*	1.17	0.08	0.04	0.02	*1.31*	*Pt-Fe alloy* ††

n.b. Sample numbers relate to numbers used in Figures 3 and 4. *Cabri & Laflamme (1974) **Razin *et al.* (1973) †Co not detected ††*not x-rayed*





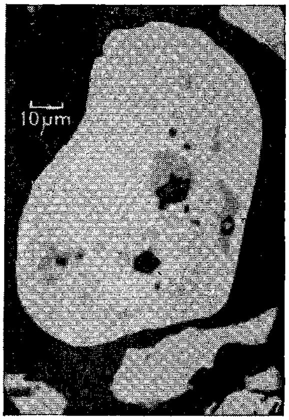


FIG. 5. Back-scattered electron image of a typical concentrically layered platinoid grain, revealing a core of osmium (white) enclosed by an alloy of Os+Ir+Pt (grey). The outermost layer, an intergrowth of Pe-Fe alloy and osmiridium, is a texture common for these two minerals throughout the Witwatersrand samples.

FIG. 6. Back-scattered electron image illustrating regular alternating layers of Pt-Fe alloy and osmiridium giving rise to a well-developed intergrowth texture. Sperrylite is attached to the top of the grain.

FIG. 7. Back-scattered electron image of a grain of isoferroplatinum (white) containing inclusions of michenerite (grey).

deposits gave a range of compositions up to a maximum of about 48 at.% (Fe + Cu + Ni), whereas Razin *et al.* (1973) report on a grain with 61.2 at.% (Fe + Cu + Ni). Table 4 illustrates the small range of compositions obtained for different grains from the same Witwatersrand mine. *X*-ray diffraction analyses of the alloys from different deposits revealed that they have one of three patterns — face-centered cubic, primitive cubic, or tetragonal — corresponding to the patterns obtained for the synthetic alloys. The *x*-ray powder patterns for four of these natural alloys are given in Table 5 and the cell edges for nine cubic specimens and cell volumes for ten specimens are plotted, against their compositions, in Figures 3 and 4, respectively.

It is apparent that the unit-cell edges (or volumes) of the natural alloys having a face-centered cubic *x*-ray diffraction pattern bear a reasonably close relationship to the regression line derived from pure synthetic face-centered cubic alloys. There is especially good agreement for samples 7* and 9, which relate to a major extension of the experimentally derived linear relationship.

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*The unit cell of sample 7 was incorrectly printed in Cabri *et al.* (1973); the correct value is *a* = 3.847(2)Å.

TABLE 3. ELECTRON PROBE ANALYSES OF ISOFERROPLATINUM IN HEAVY MINERAL CONCENTRATES FROM GOLD MINES OF THE ANGLO AMERICAN CORPORATION OF SOUTH AFRICA

Mine	Weight Per Cent									Atomic Proportions	
	Pt	Ir	Os	Ru	Ni	Fe	Rh	Cu	Total	P.G.E.*	Fe+Ni+Cu
S.A. Lands	80.0	2.0	<0.1	0.6	0.3	8.5	3.8	0.6	95.8	0.735	0.265
E. Daggafontein	83.8	2.8	0.8	0.1	0.3	9.8	---	---	97.6	0.713	0.287
Western Deep Levels 1	86.4	1.3	<0.1	2.1	<0.1	9.4	1.1	0.7	101.0	0.729	0.271
2	80.5	2.2	0.8	3.8	0.2	8.5	2.8	---	98.8	0.760	0.240
Vaal Reefs North	86.2	1.6	0.6	0.5	0.2	8.9	---	---	98.0	0.738	0.262
South	84.7	1.7	2.1	0.9	0.3	9.1	---	---	98.8	0.734	0.266
Free State Geduld	81.5	3.4	1.8	0.2	0.2	9.5	---	---	96.6	0.720	0.280
Welkom	89.4	0.7	0.8	0.2	0.4	8.2	0.6	0.3	100.6	0.750	0.250
Western Holdings 1	88.2	0.7	0.4	0.5	0.2	8.2	1.7	0.2	100.1	0.758	0.242
2	87.2	1.3	0.5	<0.1	0.2	8.9	1.2	0.5	99.8	0.733	0.267
President Steyn	87.8	0.1	0.2	1.2	0.3	9.5	---	---	99.1	0.726	0.274
President Brand	88.0	1.0	0.4	0.2	0.5	7.8	0.9	0.4	99.2	0.752	0.248
Average**	85.31	1.57	0.70	0.86	0.26	8.86	1.73	0.45	99.78	0.737	0.263

* P.G.E. = platinum-group elements

** This is the composition used in Figures 3 and 4 for Sample No. 4.

n.b. The analyses given in the table are averages of a number of determinations on several selected grains in each concentrate for a total of 55 grains.. There are two averages given for Western Deep Levels and Western Holdings because they are for two concentrates separated by a time interval.

TABLE 4. ELECTRON PROBE ANALYSES OF ISOFERROPLATINUM IN HEAVY CONCENTRATE FROM PRESIDENT STEYN GOLD MINE

Grain	Weight Per Cent						
No.	Pt	Ir	Os	Ru	Ni	Fe	Total
F22	88.7	<0.1	0.5	0.2	0.3	10.1	99.8
F23	85.9	<0.1	0.1	4.9	0.1	7.5	98.5
F24	87.5	0.1	<0.1	0.1	0.4	10.7	98.8
F25	86.3	<0.1	0.2	2.5	0.4	9.3	98.7
F26	87.6	0.9	0.2	0.1	0.5	11.5	100.8
F30	89.8	<0.1	0.4	0.4	0.3	8.4	99.3
F31	88.8	<0.1	<0.1	0.1	0.2	9.2	98.3
Average	87.8	0.1	0.2	1.2	0.3	9.5	99.1

The natural alloys with the primitive cubic *x*-ray diffraction pattern also fit reasonably well with the experimentally derived straight line. In this case, however, all samples (except No. 8) cluster closely around the ideal composition Pt_3Fe. Sample No. 8 was taken from Razin *et al.*'s (1973) sample No. 17. We have re-indexed their *x*-ray data as primitive cubic and obtained an average cell edge of $a = 3.816(10)$Å, which is the value used in Figures 3 and 4. This value is also close to a hypothetical extension of the experimentally derived linear relationship for primitive cubic alloys. It seems possible, therefore, that this sample may be a platinum-rich variety of an ordered alloy having an ideal composition of $PtFe_3$.

Thus it has been shown that natural platinum-iron alloys, from a wide variety of geological environments, show similar relationships between their compositions and *x*-ray powder diffraction patterns. Deviations from the experimentally derived straight lines may be due to the conflicting effects, on the unit-cell, of atoms having ionic sizes differing from those of Pt and Fe (*i.e.* Ir, Cu, Ni, *etc.*), to possibly poor crystallinity in some samples, and to the unknown effects of cold-working on their crystal structures.

Inspection of the estimated observed intensities in Table 5 reveals some differences between closely-related materials. The observed intensities for the 100 and 110 reflections, for example, are different for synthetic ordered Pt_3Fe and the natural ordered alloy isoferroplatinum. This difference may be due, in part, to systematic intensity errors because of incomplete powder diffraction simulation by the Gandolfi camera. Another source of error may arise simply from attempting to quantify visually observed intensities for films which have different backgrounds. However, it is also possible that these differences are due to incomplete order in isoferroplatinum.*

A schematic phase diagram for the partial system Pt-PtFe may now be proposed on the

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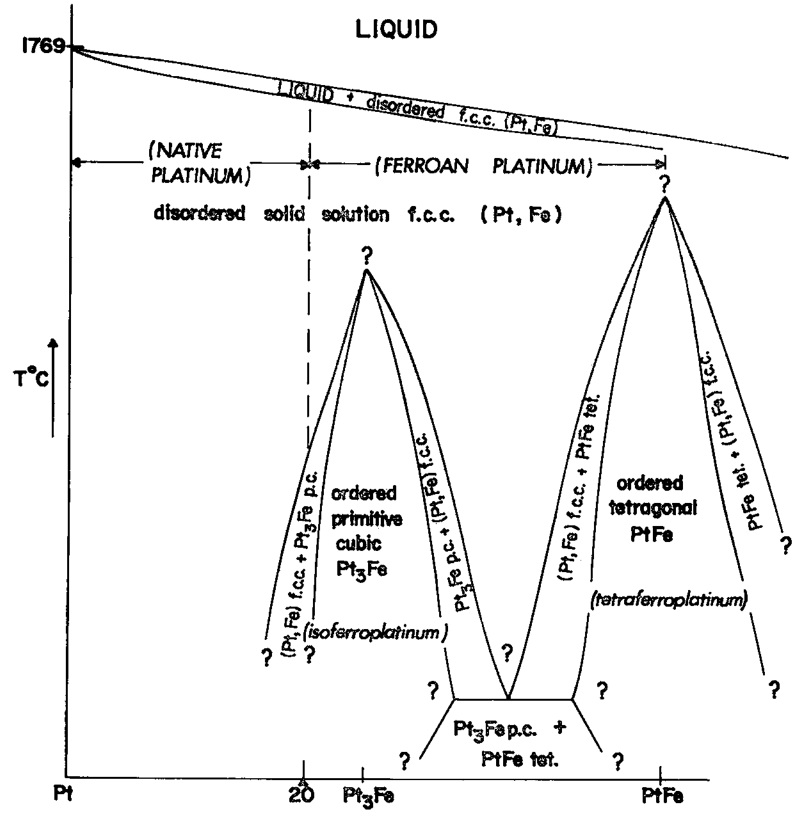
*We are grateful to Dr. A. Kato of the National Science Museum, Tokyo, for this suggestion.

TABLE 5. X-RAY POWDER DATA FOR SYNTHETIC AND NATURAL PLATINUM-IRON ALLOYS

	Synthetic Pt[1]			Synth. $Pt_{3.2}Fe_{0.8}$[2]			Native Platinum[3]			Synth. Pt_3Fe[4]			Isoferroplatinum[5]			Ferroan Platinum[6]			Synthetic PtFe[7]			Tetraferroplatinum[8]			
	a 3.9231			*a* 3.877(1)			*a* 3.877(3)			*a* 3.866(1)			*a* 3.864(1)			*a* 3.816(2)			*a*3.847(1)*c*3.715(1)			*a*3.850(5)*c*3.693(6)			
hkl	*I*	d_{meas}	d_{calc}	*I*	d_{meas}	d_{calc}	*I*	d_{meas}	d_{calc}	*I*	d_{meas}	d_{calc}	*I*	d_{meas}	d_{calc}	*I*	d_{meas}	d_{calc}	*I*	d_{meas}	d_{calc}	*I*	d_{meas}	d_{calc}	*hkl*
100										2	3.852	3.866							3	3.690	3.715	1	3.69	3.693	001
110										3	2.736	2.733	<1	2.726	2.732				3	2.714	2.720	2	2.721	2.722	110
111	10.0	2.265	2.265	10	2.235	2.238	10	2.228	2.238	8	2.228	2.232	9	2.228	2.231	10	2.202	2.203	10	2.195	2.194	10	2.191	2.191	111
200	5.3	1.962	1.961	6	1.935	1.938	4	1.931	1.939	7	1.931	1.933	7	1.932	1.932	8	1.908	1.907	4	1.918	1.923	7b	1.920	1.925	020
																			3	1.857	1.857	1	1.842	1.846	002
							<1	1.819*					<1	1.812*											
210										3	1.725	1.729	1	1.731	1.728				3	1.707	1.708	2	1.709	1.707	021
211										3	1.578	1.578	1	1.576	1.577				3	1.534	1.534	2	1.530	1.528	112
220	3.1	1.387	1.387	6	1.370	1.370	5	1.367	1.371	7	1.365	1.367	7	1.365	1.366	6	1.348	1.349	3	1.361	1.360	<1	1.366	1.361	220
																			5	1.338	1.336	6b	1.342	1.332	022
221 300										3	1.287	1.289	2	1.289	1.288				4	1.280	1.282	<1b	1.280	1.277	030
																			2	1.243	1.238	<1b	1.230	1.231	003
310										2	1.222	1.222	1	1.219	1.222				3	1.218	1.216	<1	1.220	1.217	130
311	3.3	1.1826	1.1829	8	1.168	1.169	9	1.170	1.169	10	1.165	1.166	10	1.163	1.165	7	1.150	1.150	9	1.156	1.156	5b	1.152	1.156	311
																			6	1.127	1.127	1	1.124	1.121	113
222	1.2	1.1325	1.1325	4	1.117	1.119	3	1.120	1.119	6	1.116	1.116	6	1.115	1.115	3	1.100	1.101	6	1.098	1.097	3b	1.099	1.095	222
320										2	1.072	1.072	1	1.070	1.071				½	1.068	1.067				230
																			5	1.042	1.041	<1	1.036	1.037	023
321										4	1.033	1.033	3	1.032	1.032				6	1.018	1.017	1	1.017	1.016	132
400	0.6	0.9808	0.9808	3	0.9692	0.9692	2b	0.9697	0.9692	6	0.9670	0.9665	6b	0.9667	0.9660	1b	0.9535	0.9540	5	0.9626	0.9618				040
410										5	0.9378	0.9376	2b	0.9374	0.9372				5	0.9324	0.9311				041
411										6	0.9110	0.9112							6	0.9180	0.9157				223
																			5b	0.9088	0.9068				330
331	2.2	0.9000	0.9000	9	0.8896	0.8895										5b	0.8734	0.8735							
420	2.0	0.8773	0.8772	8	0.8670	0.8669										6b	0.8538	0.8533							
422	2.9	0.8008	0.8008	10b	0.7919	0.7914																			

All intensities estimated except for pure Pt, b = broad.
*Unknown impurity.

1. *f.c.c.*, A.S.T.M. Card No. 4-0802, Cu/Ni radiation, diffractometer.
2. *f.c.c.*, No. 428-300, Cu/Ni radiation, 57.3 mm Debye-Scherrer.
3. *f.c.c.*, $[Pt_{3.19}Pd_{0.03}Ir_{0.01}, Fe_{0.65}Cu_{0.11}Ni_{0.01}]$, Tulameen River, British Columbia, Co/Fe radiation, 57.33 mm Gandolfi (Sample 1 in Table 2).
4. *p.c.*, No. 372-300, Co/Fe radiation, 57.3 mm Debye-Scherrer.
5. *p.c.*, $Pt_{2.93}(Fe_{1.01}Sb_{0.03}Cu_{0.02}Ni_{0.01})$, Tulameen River, British Columbia, Co/Fe radiation, 57.3 mm Gandolfi (Sample 5 in Table 2).
6. *f.c.c.*, $[Pt_{2.00}Ir_{0.10}, Fe_{1.73}Cu_{0.14}Ni_{0.03}]$, Similkameen River, British Columbia, Cu/Ni radiation, 57.3 mm Gandolfi (Sample 9 in Table 2).
7. *tet.*, No. 374-300, Co/Fe radiation, 114.6 mm Debye-Scherrer, Cabri *et al.* (1973).
8. *tet.*, $(Pt_{2.06}Ir_{0.01})(Fe_{1.38}Cu_{0.49}Ni_{0.05}Sb_{0.01})$, Mooihoek, Transvaal, Co/Fe radiation, 57.3 mm Gandolfi (Sample 10 in Table 2).



SCHEMATIC DIAGRAM ILLUSTRATING ORDERED PHASES WITHIN A DISORDERED (Pt, Fe) SOLID SOLUTION FIELD

FIG. 8. Schematic diagram illustrating ordered phases within a disordered (Pt,Fe) solid-solution field.

basis of the study of synthetic and natural platinum-iron alloys (Figure 8). Thus, at high temperatures beneath the liquidus, a continuous disordered solid solution with a face-centered cubic pattern is thought to occur. At some unknown lower temperature, or temperatures, ordering occurs near the compositions Pt_3Fe and PtFe (as described in an earlier section) resulting in a primitive cubic and a tetragonal phase, respectively. It is possible that the composition of these alloys has a greater effect on their crystal structures (assuming no cold-working effects) than do their annealing histories because we have shown that grains from the Tulameen and Similkameen rivers placer deposits are either *f.c.c.*, or *p.c.*, apparently dependent on their iron content.

NOMENCLATURE OF PLATINUM-IRON ALLOYS

The understanding of the phase relations discussed above permits us to propose a nomenclature for the natural platinum-iron alloys. This nomenclature applies to platinum-iron alloys which may contain minor or trace amounts of other elements such as Ir, Cu, Ni, *and* whose structures have been determined by *x*-ray analysis. Because it is not often possible to obtain an *x*-ray analysis of such minerals, it is further proposed that those platinum-iron alloys whose structures have *not* been determined by *x*-ray analysis be referred to by the general name *platinum-iron alloy**. This follows the usage previously employed by Page *et al.* (1972).

The other proposals are:

a) *native platinum* — for disordered face-centered cubic platinum alloys which contain 80 or more at.% Pt. This is consistent with the

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*Use of the general term "iron-bearing platinum", introduced by Cabri *et al.* (1973), should be discontinued because its translation in some languages is identical to that of ferroan platinum (see b).

terminology of Harris & Cabri (1973) for native osmium, iridium, and ruthenium and as used by Cabri & Hey (1974).

b) *ferroan platinum* — for disordered face-centered cubic platinum-iron alloys, a variety of native platinum (Pt,Fe), with Fe between 20 and 50 at.%. Minor amounts of Ir, Rh, *etc.* are considered as Pt and minor amounts of Cu, Ni, *etc.* are considered as Fe. The high-iron varieties will have increasing magnetic susceptibility.

c) *isoferroplatinum* — for ordered primitive cubic platinum-iron alloys, with compositions usually near Pt_3Fe, minor amounts of Ir, Rh, *etc.* are considered as Pt and minor amounts of Cu, Ni, *etc.* are considered as Fe. This is a newly characterized *species* and its compositional limits are not known exactly. Table 6 illustrates an application of this nomenclature. Four grains have compositions close to ideal Pt_3Fe, even though they contain varying proportions of minor elements, and, because they are primitive cubic, may be called isoferroplatinum. The fifth grain, however, contains a total of 82.1 at.% platinum-group elements (PGE) and, without *x*-ray study, might have been thought to be native platinum. The primitive cubic pattern obtained identifies it also as isoferroplatinum. The large quantity of Rh, in this case, may have had some influence on the structure (and on the cell dimensions) but the mineral is still principally a Pt and Fe alloy. This example shows how the nomenclature may be applied and also stresses that the compositional range, as illustrated in the schematic diagram (Fig. 8), is not known precisely.

Cold-working (*e.g.* during mineral beneficiation) may produce ferromagnetism in the mineral and disordering of the primitive cubic structure to face-centered cubic. It is not known precisely what are the effects of order-disorder on the hardness of such alloys. Ramdohr (1969, p. 345) reports that "Naturally occurring placer platinum is appreciably harder than commercial platinum with the same composition; the difference is due to "cold-working" during fluvial transport, as pointed out by Zemczuzny (1920)." It is doubtful that this comparison was made on grains which had been microanalysed and *x*-rayed, but it still should serve as a caution against making microhardness tests on such alloys without knowing *both* the exact composition *and* the structure.

d) *tetraferroplatinum* — for ordered tetragonal platinum-iron alloys, with compositions usually near PtFe, and again with minor Ir, Rh, *etc.* considered as Pt and minor Cu, Ni. *etc.* considered as Fe. This is a redefined species which probably corresponds to the "ferroplatinum" of Mikheev *et al.* (1961), and the "tetragonal ferroplatinum" of Genkin & Basova (1965) and Razin *et al.* (1973). The mineral is thought to be ferromagnetic and is weakly anisotropic under oil immersion. It is best differentiated from the encapsulated Pt-Fe alloys by electron back-scatter images with the electron probe.

Invalid names.

i) *polyxene* (or polyxen) is no longer considered a valid species or varietal name. Depending on the author, as shown in Table 1, some "polyxenes" may be native platinum, ferroan platinum, isoferroplatinum, or just platinum-iron alloy.

ii) *ferroplatinum* (or tetragonal ferroplatinum) is no longer considered a valid species name. This proposal will probably meet with the most resistance, especially in certain segments of the mining industry, where it is used as a general term for platinum alloys. It is hoped, however, that the shorter term "Pt-Fe alloy" will be used instead for these incompletely characterized alloys, thus avoiding confusion with the different applications of the term "ferroplatinum" listed in Table 1.

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TABLE 6. ELECTRON PROBE ANALYSES OF ISOFERROPLATINUM IN HEAVY CONCENTRATE FROM WESTERN HOLDINGS MINE

Grain	Weight Per Cent									Atomic Proportions										
No.	Pt	Ru	Rh	Ir	Os	Fe	Ni	Cu	Total	Pt	Ru	Rh	Ir	Os	Σ	Fe	Ni	Cu	Σ	Unit-cell(A)
1	87.4	0.58	0.67	3.0	0.19	8.1	0.12	0.28	100.34	2.85	0.04	0.04	0.10	0.01	*3.04*	0.92	0.01	0.03	*0.96*	3.868(8)
2	87.8	1.1	0.77	0.18	0.19	8.7	0.06	0.28	99.08	2.85	0.07	0.05	0.005	0.006	*2.981*	0.98	0.01	0.03	*1.02*	3.865(4)
3	85.9	3.1	2.4	0.40	0.78	7.0	0.04	0.43	100.05	2.88	0.20	0.01	0.014	0.03	*3.134*	0.82	0.004	0.04	*0.864*	3.868(10)
4	90.5	0.8	0.08	0.17	0.59	9.1	0.02	0.14	101.40	2.89	0.05	0.005	0.005	0.02	*2.97*	1.02	--	0.01	*1.03*	3.870(2)
5	83.2	2.2	5.7	0.99	0.90	5.7	0.30	0.30	99.29	2.72	0.14	0.36	0.04	0.03	*3.29*	0.65	0.03	0.03	*0.71*	3.861(2)

n.b. All five grains have the primitive cubic structure.

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