The Ala-Penikka PGE Reefs in the Penikat Layered Intrusion, Northern Finland

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With 7 Figures

Summary

The PGE mineralized zones referred to as the Ala-Penikka PGE Reefs (AP I and AP II) are located about 250 m and 340 m above the base of megacyclic unit IV in the Penikat layered intrusion, both mineralizations being hosted by plagioclase-augite-bronzite and narrow poikilitic plagioclase cumulates. A depression structure (pothole) about 300 m long and 100 m deep is encountered in the area of the AP I Reef, and it is in this structure that the AP I Reef, which is normally 30 cm thick, attains its maximum thickness of 20 m.

The dominant sulphide paragenesis in AP I is pyrrhotite-chalcopyrite-pentlandite-pyrite and that in AP II chalcopyrite-pentlandite-pyrite. The platinum-group minerals identified comprise almost thirty species, the most common being Pd-Te-(Bi) and Pd-As-Sb minerals and sperrylite ($PtAs_2$).

The AP Reefs are interpreted as having been formed from an upward-migrating fluid-enriched intercumulus melt in which PGE, S, Ni, Cu and related elements occurred in the fluid phase. The poikilitic plagioclase cumulate in both of the AP Reefs acted as a layer which trapped the upward-migrating intercumulus melt at its lower contact. The depression structure developed when a disturbance of some kind in the magma chamber caused the unconsolidated cumulate layers to collapse.

Zusammenfassung

Die PGE Reefs von Ala-Penikka in der Penikat-Intrusion, Nord-Finnland

Die als Ala-Penikka Platin Reefs (AP I und AP II) bezeichneten vererzten Zonen liegen ungefähr 250 m und 340 m oberhalb der Basis der vierten megazyklischen Einheit in der Penikat-Intrusion. Beide Vererzungen kommen in Plagioklas-Augit-Bronzit und

dünnen Bändern poikilitischer Plagioklas-Kumulate vor. Eine Depressions-Struktur (Pothole) von etwa 300 m Länge und 100 m Tiefe kommt im Bereich des AP I Reefes vor. Hier erreicht das AP I Reef, das durchschnittlich nur 30 cm mächtig ist, seine maximale Mächtigkeit von 20 m.

Die wichtigste Sulfidparagenese in AP I ist Magnetkies-Kupferkies-Pentlandit-Pyrit, und die in AP II Kupferkies-Pentlandit-Pyrit. An die dreißig verschiedene Platin-Minerale konnten identifiziert werden; die verbreitetsten sind Pd-Te-(Bi) und Pd-As-Sb Minerale, sowie Sperrylit ($PtAs_2$).

Die AP-Reefs haben sich aus einer aufwärts migrierenden Fluid-angereicherten Interkumulusschmelze gebildet, in der PGE, S, Ni, Cu und assoziierte Elemente in der fluiden Phase vorkommen. Das poikilitische Plagioklas-Kumulat in beiden AP Reefs fungierte als eine Barriere die für die aufwärts migrierende Interkumulusschmelze undurchlässig war. Eine Störung in der Magmenkammer, die die noch nicht konsolidierten Kumulat-Lagen betraf, wird für die Entstehung der Depressions-Struktur verantwortlich gemacht.

Introduction

Exploration for chrome and nickel ores carried out by *Outokumpu Oy* in the area of the Penikat layered intrusion in the early 1960's eventually led to the discovery of a low-grade sulphide occurrence at Ala-Penikkavaara (Fig. 1), which was not analysed for platinum-group elements (PGE). In summer 1981 this same occurrence was sampled again by J. Lahtinen for the purposes of PGE analysis, and the results proved promising in that all the samples contained some amount of PGE and the best as much as 4.5 ppm platinum, 14.6 ppm palladium and 1.0 ppm gold. On the resumption of exploration in the area the following summer this zone was found to continue for the entire 23 km length of the intrusion, and later, in summer 1983, a second PGE occurrence was identified in the Ala-Penikka area 90 metres higher up in the layered series.

These two mineralized zones enriched in platinum-group elements are located in the lower part of megacyclic unit IV, about 800 and 900 metres above the base of the Penikat layered intrusion (Figs. 2 and 3 and *Alapieti* et al., Figs. 3 and 4, this volume). The lower PGE zone is referred to as the Ala-Penikka I Reef (AP I) and the upper one the Ala-Penikka II Reef (AP II), after their initial sites of identification. The AP Reefs have previously been described by *Alapieti* and *Lahtinen* (1986), *Halkoaho* (1989) and *Halkoaho* et al. (1989).

Petrography and Subdivision of the Lower Part of Megacyclic Unit IV

Megacyclic unit IV is located at a structural height of between 550 and 1550 metres in the Penikat stratigraphy in the Ala-Penikka block (*Alapieti* et al., Fig. 4, this volume). The lower part of this unit, as described in this paper, comprises a cumulate sequence located 550–1200 metres above the base of the layered intrusion. It is divided into four subzones (Figs. 2 and 3), mainly by reference to the cryptic variation in augite (Fig. 4).

The first subzone, which is 100 metres thick, begins with olivine cumulates or bronzite cumulates, which host the Sompujärvi PGE deposit (*Halkoaho* et al., this
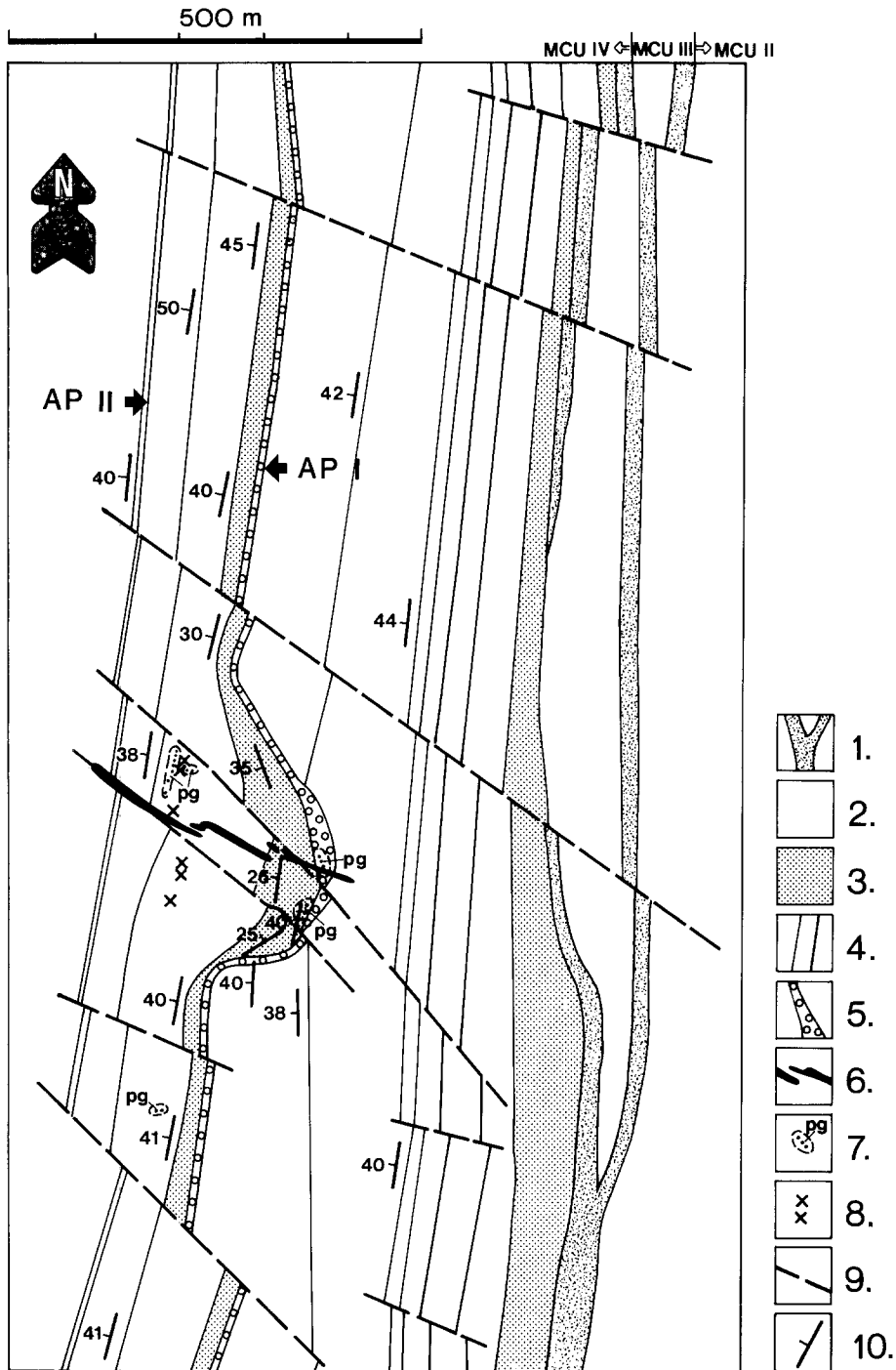
Fig. 1. Generalized geological map of the Ala-Penikka area. *1* Peridotitic-pyroxenitic cumulates; *2* Plagioclase-bronzite-augite cumulate; *3* Plagioclase-bronzite cumulate with intercumulus augite; *4* Anorthositic interlayers; *5* Poikilitic plagioclase mesocumulate with intercumulus augite and bronzite; *6* Diabase dike; *7* Pegmatoids; *8* Anorthositic fragments; *9* Fault; *10* Strike and dip of layering; *AP I* AP I Reef; *AP II* AP II Reef; *MCU II* megacyclic unit II; *MCU III* megacyclic unit III; *MCU IV* megacyclic unit IV
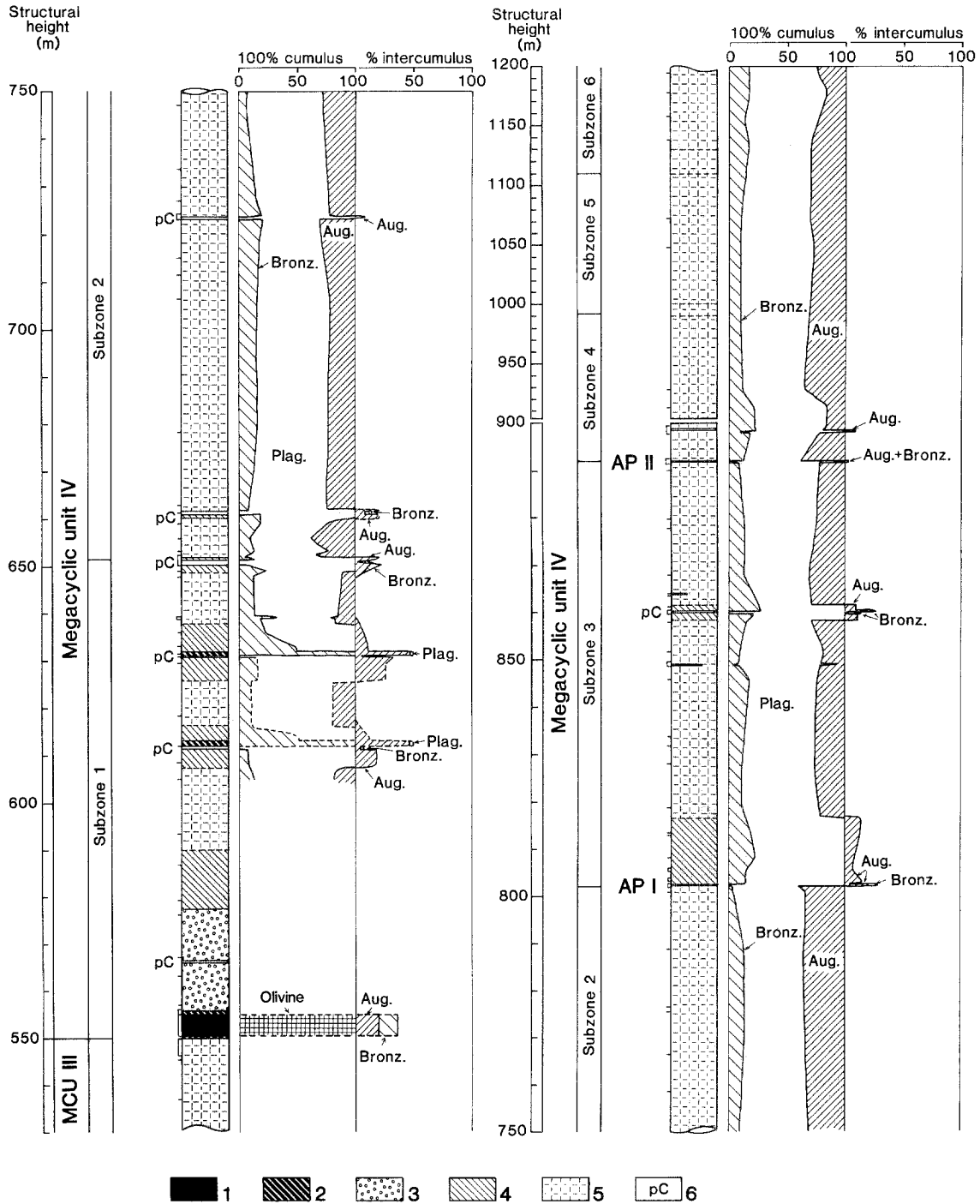
Fig. 2. Stratigraphic sequence, subzones, and modal data on the proportions of cumulus and intercumulus minerals in the lower part (550–1200 m) of megacyclic unit IV. The amount of the cumulus minerals has been normalized to 100 vol.%, whereas the amount (%) of the intercumulus minerals represents the modal composition of the rock. *1* Olivine ± bronzite cumulate with intercumulus augite ± bronzite; *2* Bronzite cumulate with intercumulus augite ± plagioclase; *3* Poikilitic plagioclase-bronzite orthocumulate with intercumulus augite; *4* Plagioclase-bronzite mesocumulate with intercumulus augite; *5* Plagioclase-augite-bronzite adcumulate; *6* Plagioclase adcumulate or mesocumulate with intercumulus augite and bronzite; *AP I* AP I Reef and *AP II* AP II Reef
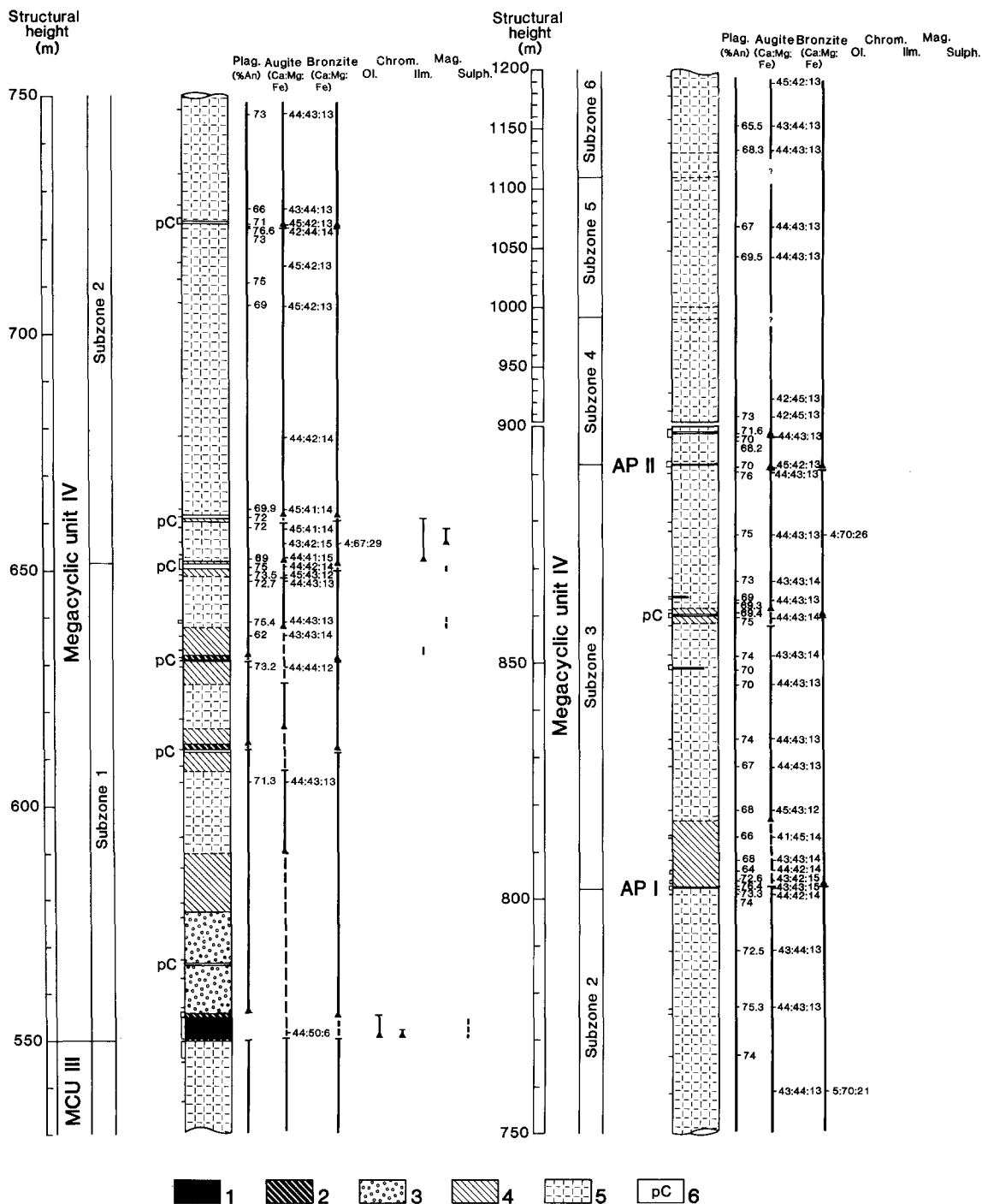
Fig. 3. Stratigraphic sequence and cryptic variation in minerals in the lower part (550–1200 m) of megacyclic unit IV. Continuous vertical lines indicate cumulus minerals and broken vertical lines intercumulus minerals. *Plag.* plagioclase; *Ol.* olivine; *Chrom.* chromite; *Ilm.* ilmenite; *Mag.* magnetite; *Sulph.* sulphides. For key to legend, see Fig. 2

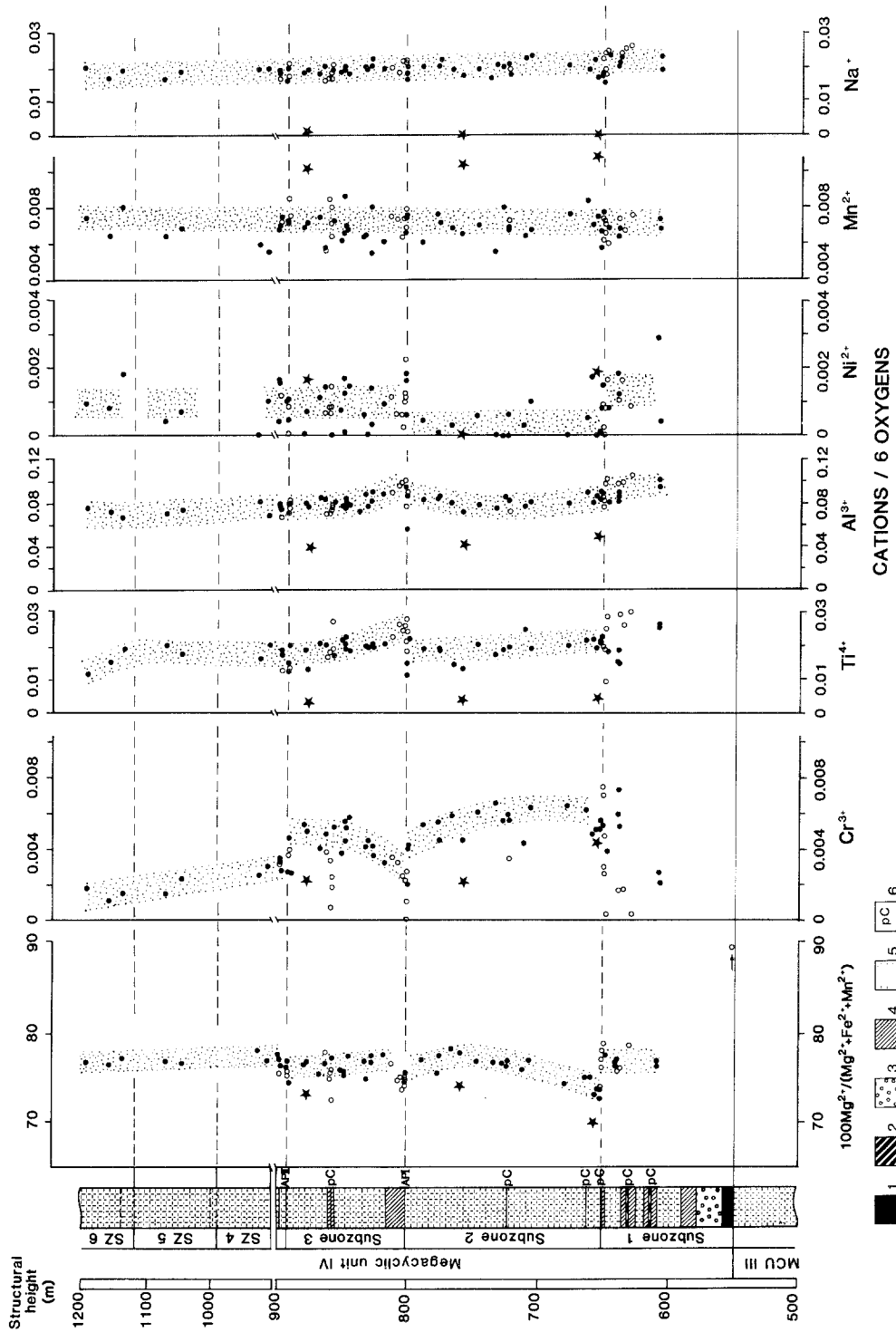Fig. 4. $100Mg^{2+}/(Mg^{2+} + Fe^{2+} + Mn^{2+})$ ratio and selected cation contents for Ca-rich (filled circle is cumulus and open circle intercumulus) and Ca-poor (star) pyroxenes in the lower part of megacyclic unit IV. For key to legend, see Fig. 2

volume). These ultramafic rocks are overlain by a sequence of gabbronoritic cumulates, first plagioclase-bronzite and then mainly plagioclase-augite-bronzite cumulates, with some anorthositic and pyroxenitic interlayers (Figs. 2 and 3).

The second subzone, 150 metres thick, is mainly composed of homogeneous plagioclase-augite-bronzite cumulates (Figs. 2 and 3). The third subzone, 90 metres in thickness, begins with a thin, 3–30 cm thick layer of poikilitic plagioclase mesocumulate in which augite and bronzite occur as a poikilitic oikocrysts. Above this layer is 1 m thick poikilitic plagioclase-bronzite mesocumulate in which only augite occurs as poikilitic oikocrysts. This rock is overlain by 13 m of a gabbronorite in which augite still occurs as the intercumulus mineral but no longer in oikocrysts. Above this rock type is a fairly homogeneous plagioclase-augite-bronzite adcumulate (Figs. 2 and 3).

The fourth subzone is interpreted here as being almost 300 m thick. It is poorly exposed, and may be divided into three parts on the basis of geophysical evidence, so that it could probably be held to contain a fifth and a sixth subzone. It begins with a thin layer of poikilitic plagioclase adcumulate, which is overlain by a thick sequence of plagioclase-augite-bronzite adcumulate. The putative fifth and sixth subzones are composed of plagioclase-augite-bronzite adcumulates (Figs. 2 and 3).

Depression Structure

A depression structure or 'pothole' about 300 m long and 100 m deep which cross-cuts the underlying cumulates is encountered at the border between the second and third subzones (Fig. 1). The cumulus stratigraphy of this depression structure greatly resembles that of the normal Reef, but the vertical thicknesses of the layers are greater. The poikilitic plagioclase mesocumulate, for example, is now 2 to 20 m thick. The area also features large amounts of gabbroic pegmatoids.

Platinum-group Element Mineralizations

The AP I and AP II Reefs are located at the border between the second and third subzones and in the upper part of the third subzone, respectively (Figs. 2 and 3).

The AP I Reef is usually 30 cm thick, and the mineralization is erratic in its distribution within it, being located in the uppermost part of the plagioclase-augite-bronzite orthocumulate at the top of the second subzone and continuing upwards into the poikilitic plagioclase mesocumulate at the base of the third subzone (Fig. 5A). Base metal sulphides and platinum-group minerals usually occur in the interstices of the cumulus framework in these rocks together with magnetite. The platinum-group elements and sulphides are concentrated over a wider zone at the site of the depression structure, so that the mineralized rocks attain a vertical thickness of almost 20 metres (Fig. 5B).

The distribution of the mineralization in the AP II Reef greatly resembles that in AP I, base metal sulphides and platinum-group minerals being located in the uppermost part of the plagioclase-augite-bronzite orthocumulate at the top of the third subzone and continuing upwards into the narrow poikilitic plagioclase adcumulate at the base of the fourth subzone (Figs. 2 and 3). It is generally quite poor in sulphides, with the exception of certain smallish concentrations where the sulphide content rises to 1–2 vol.% and the PGE content to some tens of ppm.
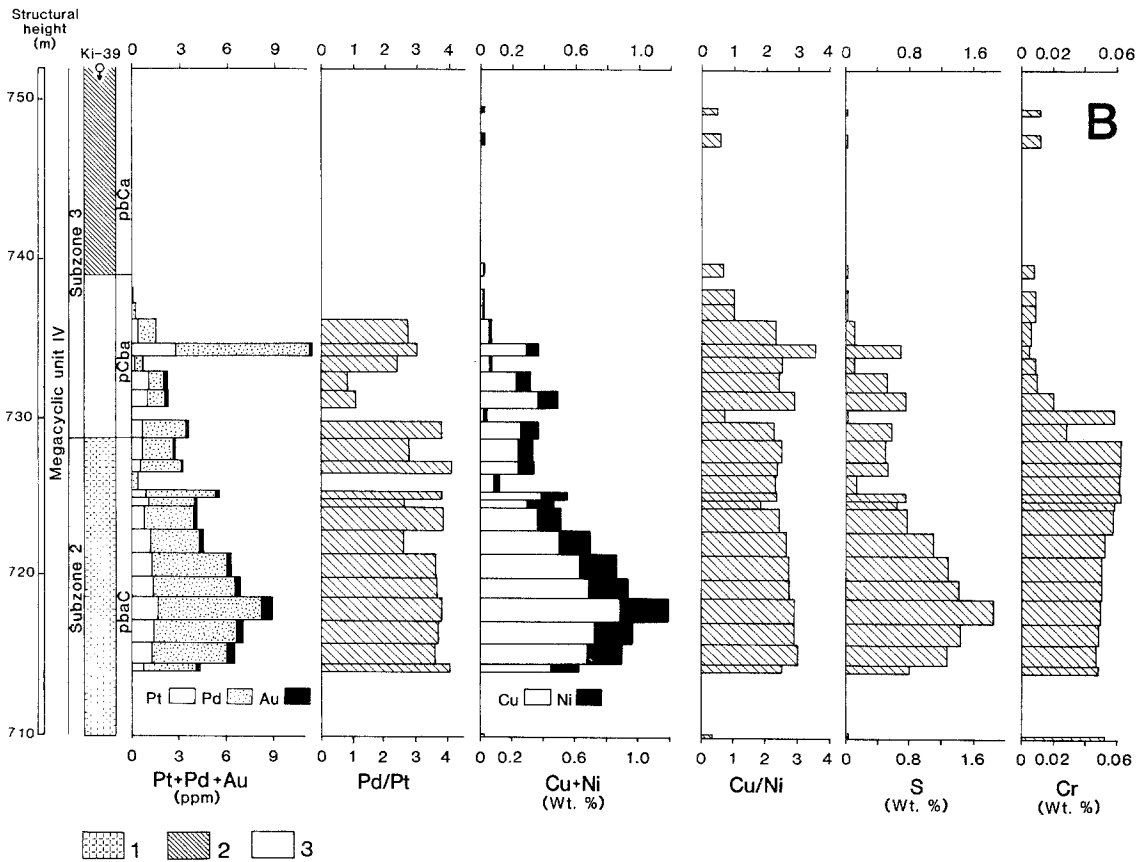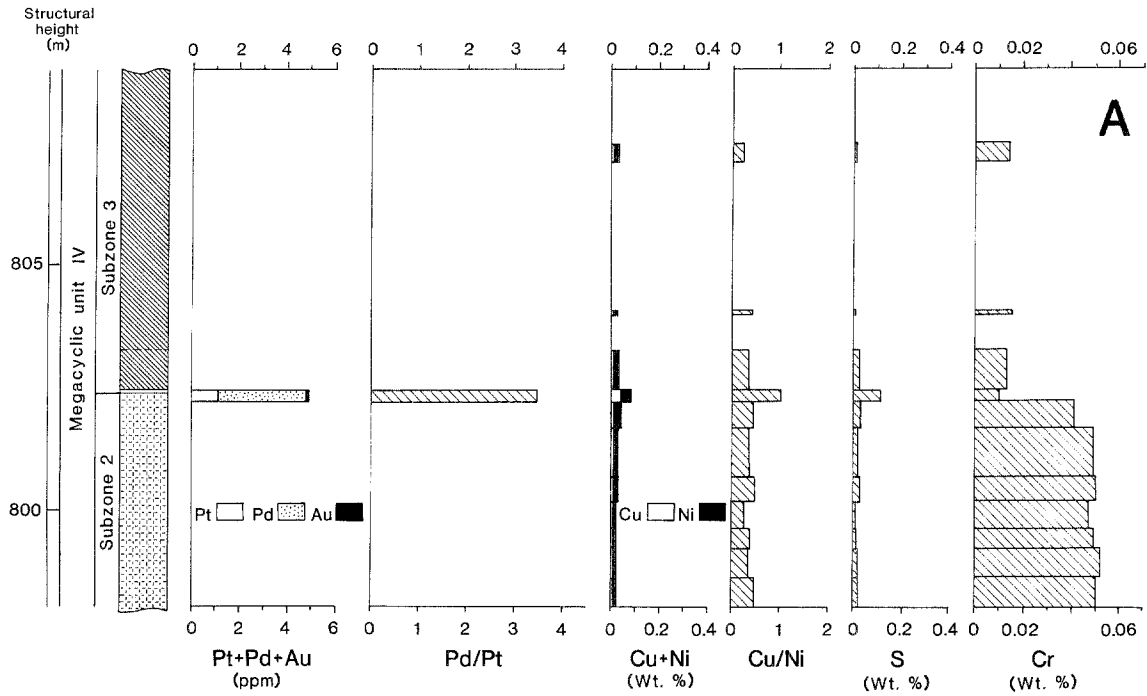
Fig. 5. Stratigraphic sequence of the normal AP I Reef (A) and the AP I Reef in the depression structure (B) showing variations in bulk Pt + Pd + Au, Cu + Ni, S and Cr (Cu, Ni and S determined by XRF), and in the Pd/Pt and Cu/Ni ratios. *1* Plagioclase-augite-bronzite cumulate (pabC); *2* Plagioclase-bronzite mesocumulate (pbCa); *3* Poikilitic plagioclase meso-cumulate (pCab)

Mineralogy

The main primary minerals in the area are olivine, Ca-poor and Ca-rich pyroxene and plagioclase, with minerals of the spinel group and ilmenite also frequently encountered. Sulphides are present mainly in the AP I and AP II mineralized zones (for analytical method, see *Halkoaho* et al., this volume).

Olivine

No fresh, unaltered olivine has yet been encountered anywhere in the whole of the Penikat intrusion, since it has been altered throughout to chrysotilic serpentine and magnetite. On the basis of its pseudomorphs, olivine seems to have been a typical cumulus mineral the middle part of the ultramafic cumulates at the base of mega-cyclic unit IV.

Pyroxenes

The Ca-poor pyroxenes are represented by bronzite and the Ca-rich pyroxenes by augite (Figs. 2 and 3).

Bronzite.   Unaltered, primary orthopyroxene has only been encountered in a few samples. On the basis of these, and also considering the pseudomorphs, it can be said to occur almost always as a cumulus mineral. Exceptions are formed by the ultramafic cumulates, where it may occur partly as an intercumulus and partly as a cumulus phase, and the most anorthositic interlayers, where it occurs as an intercumulus phase (Figs. 2 and 3).

Augite.   The subdivision of the lower part of megacyclic unit IV into four subzones is based on the variation in augite composition (Fig. 4). The average $100Mg/(Mg + Fe + Mn)$ ratio of the augites in the gabbroic and anorthositic cumulates of the first subzone is 77, whereas immediately above them, in the second subzone, it drops to 75.

It is important to note, that the most Cr-rich augites among the gabbronoritic cumulates are encountered in the second subzone. The Ni^{2+} content also reveals four distinct subzones, the augites of the first and third being richer in Ni than those of the second (Fig. 4).

Plagioclase

Plagioclase is encountered in every rock type of megacyclic unit IV with the exception of the ultramafic cumulates at the base of the unit (Fig. 3). Its composition alternates as a function of structural height between low An in the gabbronorites immediately above each anorthositic interlayer and peak values in the subsequent anorthositic layers. The trend alters above the AP II Reef, however, gently decreasing from An_{73} to An_{66}, as is to be expected as a result of fractionation.

Iron-Chromium-Titanium Oxides

Cumulus chromite has been encountered in the ultramafic cumulates at the base of megacyclic unit IV. A relatively chromium-rich magnetite has been identified about

4 m above the base of the second subzone, with a Cr_2O_3 content of 6.8 wt.%. Intercumulus magnetite is typical of the AP I Reef, while ilmenite is a common minor cumulus phase, being most prominent in a layer 10 m thick located in the lower part of the second subzone (Fig. 3).

Sulphides

The highest incidence of base metal sulphides is encountered in the AP I Reef, where the sulphide content rises to 1–5 vol.%. The dominant sulphide paragenesis is
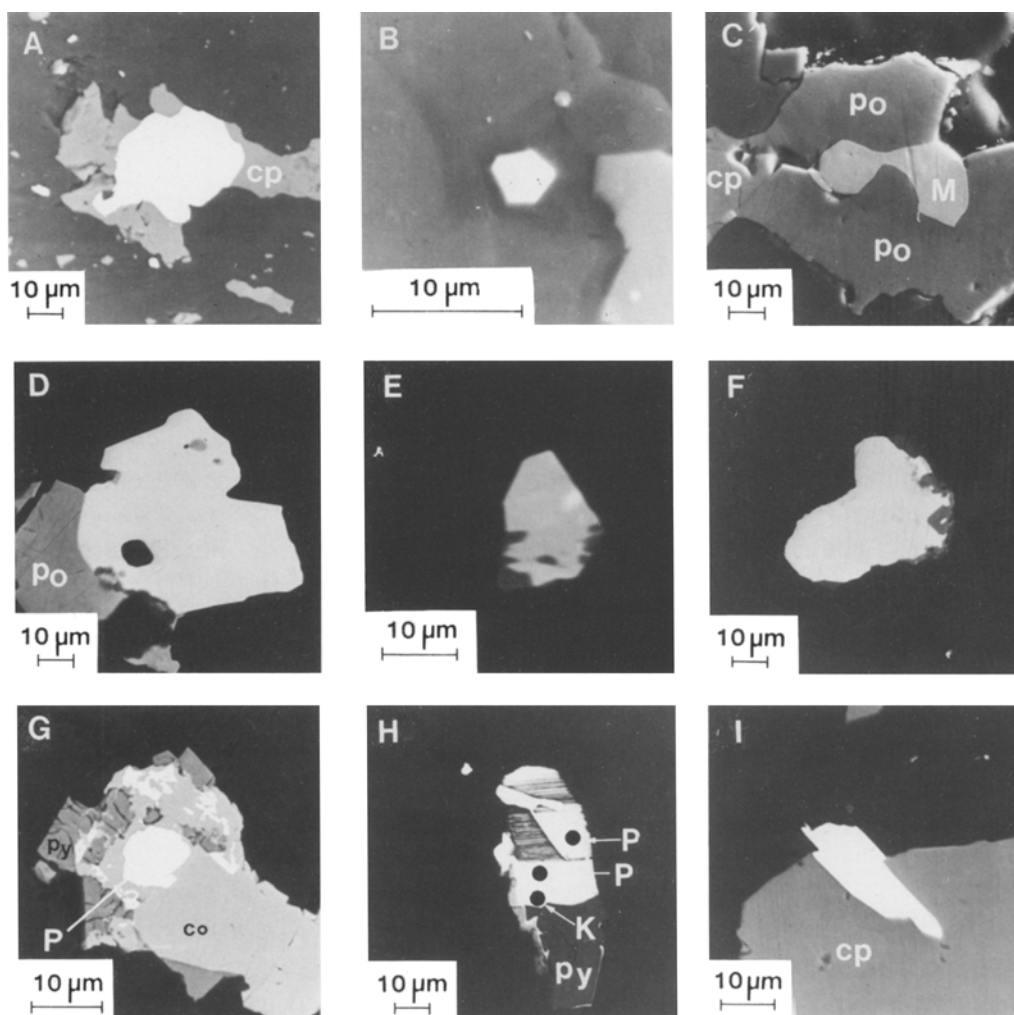

Fig. 6. Backscattered electron images showing various platinum-group minerals of the AP Reefs. Scale bars are 10 μm. A) Xenomorphic kotulskite (Pd(Te, Bi)) surrounded by chalcopyrite (*cp*) (AP I Reef, depression structure). B) Idiomorphic kotulskite in silicate (AP I Reef, depression structure). C) Merenskyite (Pd(Te, Bi)$_2$) (*M*) surrounded by pyrrhotite (*po*) (normal AP I Reef). D) Sperrylite in contact with pyrrhotite (*po*) (AP I Reef, depression structure). E) Euhedral palladoarsenide ((Pd$_2$)(As, Sb)) in silicate (AP II Reef). F) Unnamed Pd$_{1.68}$As mineral in silicate (AP II Reef). G Palladoarsenide (*P*) surrounded by cobaltite (*co*) and pyrite (*py*) (AP II Reef). H) Composite grain of kotulskite (*K*) and Pd-As mineral (*P*) (AP II Reef). I) Braggite (Pt, Pd, Ni)S at the margin of chalcopyrite (*cp*) (normal AP I Reef)

pyrrhotite-chalcopyrite-pentlandite, while other sulphides include pyrite, sphalerite, galena, cobaltite, gersdorfite and argentopentlandite, and also violarite as an alteration product of pentlandite.

The mineral paragenesis in AP II differs from that in AP I in that pyrrhotite has not yet been found and the Ni content of the violarite is higher. This may indicate that the original pentlandite was also richer in Ni in this mineralized zone (cf. *Craig* 1982).

Platinum-Group Minerals and Gold

A total of 275 precious metal-bearing minerals have been studied in the AP Reefs, representing 28 species. These minerals generally vary from 1 to 65 μm in diameter, the mean being about 7 μm. They can be classified into eight groups which, arranged in order of abundance, are as follows: (1) Pd-Te-(Bi) minerals, e.g. kotulskite (Pd(Te, Bi)) (Figs. 6A and 6B) and merenskyite (Pd(Te, Bi)$_2$) (Fig. 6C), (ii) sperrylite (PtAs$_2$) (Fig. 6D), (iii) Pd-As-Sb minerals, e.g. palladoarsenide (Pd$_2$(As, Sb)) (Figs. 6E, 6G and 6H) and an unnamed Pd$_{1.68}$As mineral (Fig. 6F), (iv) Pd-Pt sulphides, e.g. braggite ((Pd, Pt, Ni)S) (Fig. 6I), cooperite (PtS) and vysotskite (PdS), (v) RhAsS-IrAsS minerals, e.g. hollingworthite (RhAsS), (vi) Pt-Pd-Te minerals, e.g. moncheite (PtTe$_2$), (vii) Pd-As-Te minerals and (viii) Au-Ag minerals.

About 70% of the platinum-group mineral (PGM) grains studied are found to occur in association with silicates in the AP I Reef, 23% border onto base metal sulphide grains and only 7% occur as inclusions in the sulphides. In the AP II Reef about 87% of the PGM occur in silicates and 13% in association with sulphides.

Other Minerals

Apatite is a fairly rare postcumulus mineral in the lower part of megacyclic unit IV. Its chlorine content is relatively low, varying in the range 0.54 to 1.26 wt.%. Edenitic hornblende and black tourmaline are encountered in the pegmatitic rocks of the depression structure, and the latter has also been found in the poikilitic plagioclase mesocumulate in the AP I Reef. Hf-bearing baddeleyite (ZrO$_2$) has been identified in the AP I Reef.

Whole-Rock Chemistry

Variations in Major and Minor Elements

An average of 19 elements were determined for each type sample. The analytical method is presented in *Halkoaho* et al. (this volume) and the detailed vertical variations in these elements are depicted in *Halkoaho* et al. (1989, Fig. 5.13). The majority of the main components show a fairly even vertical pattern. Phosphorus and zirconium have distinct peaks in the AP I and AP II Reefs, while the first and third subzones are poorer in Cr than the second one. Variations in Cl content in the Ala-Penikka block, based on a small number of samples, are presented in Halkoaho et al., this volume, Fig. 7, where pronounced increases in whole-rock Cl content to figures as high as 270 ppm can be seen coinciding with the AP I and AP II Reefs.
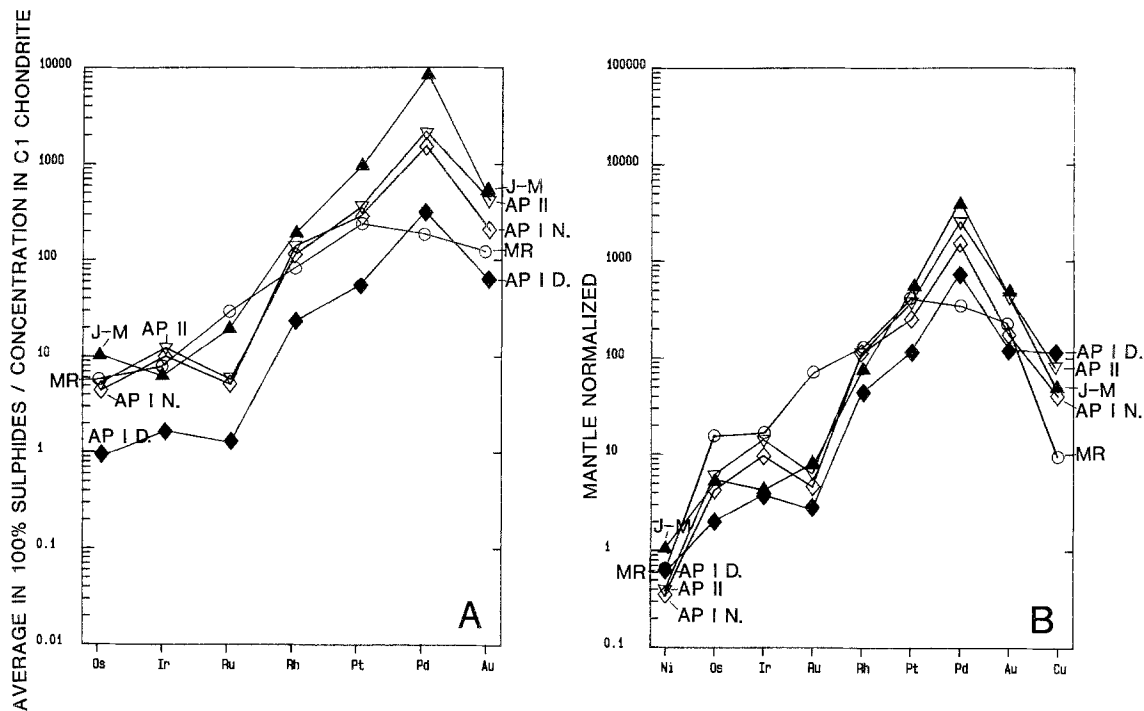
Fig. 7. Average chondrite-normalized platinum-group element and Au concentrations in the sulphide fraction data (A) and mantle-normalized platinum-group element, Au, Ni and Cu data (B) comparing the AP Reefs with the Merensky Reef (MR, data from Barnes et al., 1985 and 1988) from Bushveld and the J-M Reef (J-M, data from Barnes et al., 1985 and 1988) from Stillwater. AP I N. normal AP I Reef; AP I D. AP I Reef, depression structure; AP II AP II Reef

Ni, Cu, S, PGE and Au Concentrations in the AP Reefs

The average concentrations of nickel, copper, sulphur, platinum-group elements and gold are presented in Table 1, together with concentrations recalculated to 100 % sulphide. The vertical variations in Pt, Pd, Au, Cu, Ni and S and the Pd/Pt and Cu/Ni ratios are depicted in Fig. 5. The variation in Cr is also presented for the sake of comparison.

The recalculated concentrations indicate the obvious dominance of Cu over Ni, the Cu/Ni ratio varying in the range 1.6 to 3.9. One conspicuous feature, however, is that the Ni content in the recalculated sulphide fraction is generally lower in the depression structure than in the normal Reef, whereas the total sulphide content is higher in the depression structure. This means that the concentrations of copper and nickel are higher in the whole-rock analyses of this structure, but the PGE content lower in the sulphide fraction.

The average Pd/Pt ratio in the AP I Reef is 3.5, although it seems to be lower in the mineralized poikilitic plagioclase mesocumulate than in the underlying plagioclase-augite-bronzite cumulate. The average Pd/Pt ratio in the AP II Reef is almost the same as in the AP I. The Pd/Ir ratio is 180 on average in the AP I Reef but higher, about 240, in the AP II Reef.

The mantle-normalized metal pattern and chondrite-normalized metal concentrations in the sulphide fraction are presented in Fig. 7 and compared with data

Table 1. *Nickel, copper, sulphur, platinum-group element and gold concentrations in selected type samples representing the Ala-Penikka Reefs.* A) Whole-rock content with standard deviation in parentheses; B) Recalculated to 100 % sulphide. Metal concentrations in the Merensky Reef (*Naldrett* and *Cabri* 1976; *Barnes* et al., 1985), J-M Reef (*Naldrett*, 1981; *Barnes* et al., 1985), the Cl chondrite (*Barnes* et al., 1985) and the mantle (*Sun*, 1982; *Barnes* et al., 1988) are also shown

	Number of samples		Ni(wt.%)	Cu(wt.%)	S(wt.%)	Os(ppm)	Ir(ppm)	Ru(ppm)	Rh(ppm)	Pt(ppm)	Pd(ppm)	Au(ppm)
AP I Reef:												
Normal reef:												
Plagioclase-	4	A	0.083	0.135	0.444	0.020	0.042	0.019	0.210	1.965	7.125	0.350
augite-bronzite			(0.01)	(0.06)	(0.12)	(0.006)	(0.025)	(0.007)	(0.16)	(1.15)	(3.44)	(0.26)
cumulate		B	6.9	11.1	36.7	1.7	3.5	1.6	17.3	162.3	588.4	28.9
Poikilitic	4	A	0.033	0.090	0.138	0.016	0.043	0.035	0.237	2.615	6.150	0.140
plagioclase			(0.03)	(0.03)	(0.06)	(0.002)	(0.02)	(0.02)	(0.14)	(1.5)	(5.0)	(0.02)
mesocumulate		B	8.3	22.7	34.8	4.0	10.9	8.8	59.8	660.4	1553	35.4
Depression structure:												
Plagioclase-	4	A	0.168	0.475	0.970	0.008	0.015	0.015	0.073	0.975	2.960	0.216
bronzite-augite			(0.04)	(0.17)	(0.37)	(0.01)	(0.01)	(0.001)	(0.06)	(0.69)	(2.5)	(0.21)
cumulate		B	6.2	17.6	35.9	0.30	0.56	0.56	2.7	36.1	109.6	8.0
Poikilitic	7	A	0.074	0.227	0.523	0.009	0.018	0.017	0.094	1.083	3.417	0.144
plagioclase			(0.05)	(0.14)	(0.31)	(0.007)	(0.014)	(0.008)	(0.07)	(0.83)	(2.93)	(0.10)
mesocumulate		B	5.1	15.8	36.4	0.63	1.3	1.2	6.5	75.3	237.4	10.0
AP II Reef:												
Plagioclase-	3	A	0.060	0.200	0.352	0.026	0.063	0.038	0.220	3.400	11.367	0.607
augite-bronzite			(0.02)	(0.15)	(0.26)	(0.02)	(0.05)	(0.03)	(0.08)	(0.72)	(2.25)	(0.08)
cumulate		B	6.7	22.4	39.5	2.9	7.1	4.3	24.7	381.2	1274.3	68.0
Merensky Reef	-		-	-	-	0.063	0.074	0.43	0.24	3.74	1.53	0.31
J-M Reef	-		-	-	-	0.022	0.019	0.05	0.15	5.00	17.30	0.64
Cl chondrite	-		-	-	-	0.514	0.54	0.69	0.20	1.02	0.545	0.152
Mantle	-		0.200	0.0028	0.020	0.0042	0.0044	0.006	0.002	0.0092	0.0044	0.0014

from the Merensky Reef and J-M Reef. One conspicuous feature of all the metal patterns for the AP Reefs is the distinct negative ruthenium anomaly, although slightly smaller than in the SJ Reef at the base of the same megacyclic unit (cf. *Halkoaho* et al., this volume).

Discussion and Conclusions

Two major mineralized zones enriched in platinum-group elements, the AP I and AP II Reefs, are located about 250 and 340 metres above the base of megacyclic unit IV of the Penikat layered intrusion, both mineralizations being hosted by plagioclase-augite-bronzite and by narrow poikilitic plagioclase cumulates.

The formation of megacyclic unit IV is attributed to the entry of a new pulse of magma into the Penikat chamber which was probably slightly denser than the residual magma in the chamber and spread out across the floor. Evidence of the currents caused by this spreading of the magma across the floor is provided by the erosional contact between the ultramafic cumulates at the base of megacyclic unit IV and the gabbroic cumulates at the top of megacyclic unit III, with parts of the latter probably having been obliterated (Fig. 1, see also *Halkoaho* et al., this volume).

The residual magma intermixed with the new pulse, resulting in the hybrid magma, which was probably slightly lighter than the new primitive magma and therefore moved upwards to produce subzone 2. One indication of this is that the residual magma was probably richer in Cr than the new one, and as a result the

chromium content in the second subzone is higher than elsewhere (Fig. 4). Similarly the Mg/(Mg + Fe + Mn) ratio in the augites is lower in this subzone than elsewhere. When the magma input ceased the magma divided into convecting liquid layers.

The large depression structure (Fig. 1) is a remarkable feature as far as ore potential is concerned. It is interpreted as having developed as the result of a disturbance in the magma chamber causing the unconsolidated cumulate layers to collapse. The currents of the convection cells in the third subzone then reworked the structure and smoothed it down resulting in the formation of a regular channel-like structure. On the other hand, *Ballhaus* (1988) and *Stumpfl & Ballhaus* (1986) have come to a conclusion that the potholes of the Merensky Reef are primary disturbances and were formed where high concentrations of volatiles locally suppressed the liquidus temperature of the plagioclase so that no footwall anorthosite cumulates were formed. In the area of the Ala-Penikka depression structure large amounts of discontinuous gabbroic pegmatoids are also encountered, so that one possibility is that high volatile activity may also have interfered with the normal crystallization process in this area.

One of the most popular hypotheses to explain the mechanism for the origin of PGE deposits is that PGE concentrations are associated with base metal sulphide-bearing zones near the bases of cyclic units in sequences of cyclic layering. Since cyclic layering is generally attributed to the entry of a new magma pulse into the chamber, this suggests that the formation of these zones is genetically related to the multiple injection process (*Campbell* et al., 1983; *Irvine* et al., 1983; *Campbell* and *Turner*, 1986). In the case of the AP Reefs there are no indications of a new magma pulse, however, and only about 30% of the platinum-group mineral grains are associated with base metal sulphides, the rest occurring as inclusions in silicates. Thus this model does not seem plausible in this case.

Suggestions have also been made in recent years which highlight the role of volatiles in the formation of PGE-enriched zones in the Bushveld and Stillwater Complexes (*Ballhaus* and *Stumpfl*, 1985 and 1986; *Boudreau* et al., 1986; *Ballhaus* et al., 1988; *Boudreau*, 1988; *Mathez* et al., 1989; *Volborth* and *Housley*, 1984). This model maintains that PGE enriched zones were formed either from fluids migrating upwards (*Boudreau* et al., 1986) or from a fluid-enriched intercumulus melt from its footwall units (*Ballhaus* et al., 1988).

This kind of model is also tentatively accepted for the AP Reefs by the present authors. It is proposed that these reefs were formed from an upward-migrating fluid-enriched intercumulus melt in which sulphur, copper, nickel, PGE and other related elements (Sb, Bi, As, Te) occurred in the fluid phase. The poikilitic plagioclase cumulate acted as an impermeable layer in both the AP Reefs and trapped the migrating intercumulus melt at its lower contact. The platinum-group elements could have at least partly been derived from the residual liquid of the magma pulses from which the underlying megacyclic units were crystallized, while the copper and nickel may have originated from the second subzone, where the Ni content of the augite is distinctly lower than elsewhere (Fig. 4).

Especial thanks are due to the staff of the Institute of Electron Optics at the University of Oulu, and particularly to the head of that Department, Mr. *Seppo Sivonen*, Dipl. Eng., for their assistance with the microanalyses.

We also wish to thank *Sheila* and *Malcolm Hicks* for revising the English of this publication and translating certain parts of it, and the reviewers for their helpful comments.

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