

Platinum Metals Associated with Hydrothermal Copper Ores of the New Rambler Mine, Medicine Bow Mountains, Wyoming *

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Abstract

High concentrations of palladium and platinum (average 75 ppm and 4 ppm, respectively) are associated with copper ores at the New Rambler mine. The ore deposit is of hydrothermal origin and occurs in metagabbroic rocks at the intersection of a mylonite zone, several closely spaced faults, and a major shear zone.

Three principal mineral assemblages have been defined in the hypogene ore paragenesis: (1) an early assemblage consisting mainly of pyrite, with magnetite, pyrrhotite, pentlandite, and chalcopyrite as accessories; (2) and (3) copper-rich assemblages representing the main stage of ore deposition and consisting principally of chalcopyrite + pyrrhotite but differing in accessory platinoid and base metal minerals. Thermochemical data on mineral compatibilities suggest deposition of assemblage 1 at temperatures in the vicinity of 335°C or somewhat higher and the principal mineralization with deposition of copper- and platinoid-rich assemblages at temperatures somewhat below 335°C. Ten platinum and palladium minerals are recognized in the ore. Eight of these minerals are bismutho-tellurides or tellurides. Pt and Pd apparently occur in the ore principally as their own minerals.

A comparative study of the distribution and geochemical behavior of the precious metals Pt, Pd, Rh, Au, and Ag in the weathered portions of the deposit has shown that Pt and Rh are substantially enriched in the strongly oxidized ore horizons, possibly due to supergene processes. Pd and Ag have been extensively mobilized from the upper levels during weathering. Ag has undergone dramatic enrichment in the supergene sulfide zone, but Pd apparently has been removed from the system.

Introduction

THE New Rambler deposit is interpreted as representing a nonmagmatic accumulation of platinum-group element (PGE) and other metals that have been concentrated by processes of hydrothermal leaching of ordinary gabbroic rocks and redeposition of the leached metals along shear zones as palladium- and platinum-rich copper sulfide ore. The process is recognized by the writers as having produced small vein-type Cu sulfide occurrences rich in platinoids adjacent to mafic intrusive rocks elsewhere in the region.

Cousins (1973, p. 77) noted that "Geochemists appear to have been misled on the geochemistry of platinum group elements by overemphasis on the chemical inertness of these elements." Stumpfl (1974) has compiled convincing evidence of remobilization and redistribution of platinoids by deuteric or hydrothermal fluids in many important deposits, and it now seems generally accepted that the relatively Pd and Pt rich offset deposits at Sudbury and similar vein ores at Noril'sk represent, at least

in part, late-stage hydrothermal events in these districts. The purpose of this report is to document an instance in which platinum-group elements have been mobilized and concentrated to a remarkable degree by hydrothermal fluids at intermediate temperatures.

Geologic Setting

Regional geology

The New Rambler mine is in the Douglas Creek mining district of the Medicine Bow Mountains in southeastern Wyoming, approximately 40 miles west-southwest of Laramie. For a detailed discussion of the regional geology of the Medicine Bow Mountains, see Houston et al. (1968).

The central part of the Medicine Bow Mountains is structurally dominated by a series of northeast-trending shear zones (Fig. 1). The most prominent of these, referred to as the Mullen Creek-Nash Fork shear zone (Houston et al., 1968), constitutes a major Precambrian lineament that splits the Medicine Bow Mountains into two distinct geologic provinces. Rocks northwest of the shear zone are low-grade miogeosynclinal metasedimentary units ranging in

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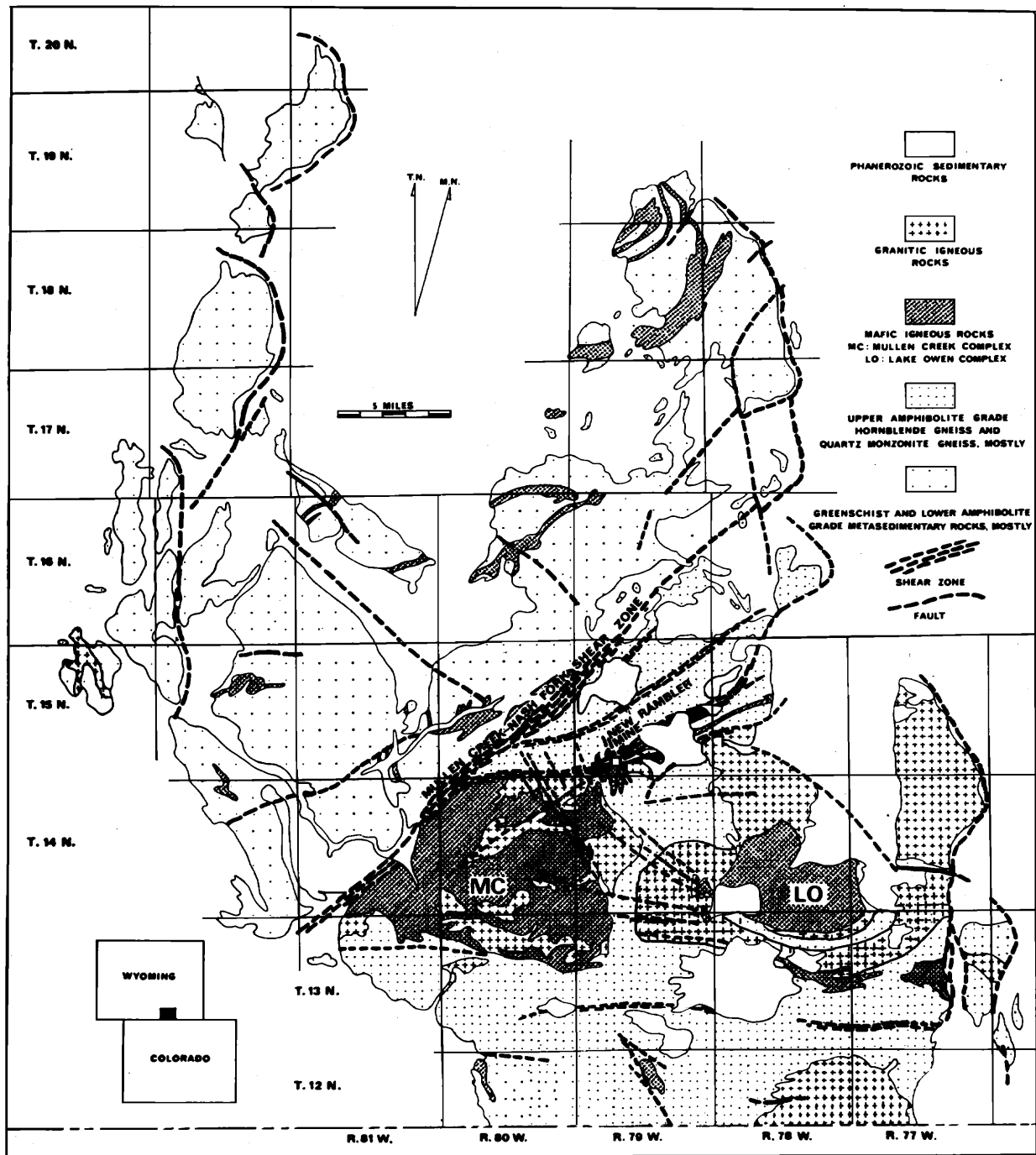


FIG. 1. Generalized geologic map of the Precambrian of the Medicine Bow Mountains, Wyoming, showing the location of the New Rambler mine with respect to the Mullen Creek-Nash Fork shear zone and layered mafic intrusive complexes.

age from at least 1,650 m.y. to approximately 2,410 m.y. (Hills et al., 1968). Precambrian rocks immediately southeast of the shear zone are continuous with the igneous-metamorphic province of central and northern Colorado. These rocks are predominantly felsic paragneisses and paragneisses metamor-

phosed to upper amphibolite grade 1,750 m.y. ago (Hedge et al., 1967) and younger Precambrian mafic and granitic intrusives which also have been partially to completely metamorphosed and subjected to varying intensities of cataclasis.

The cataclastic history of the region has been com-

plex. The large northeast-trending shear zones appear to have been initiated during the terminal stages of the 1,750 m.y. orogeny and were active intermittently through Laramide time. Shear zone rocks comprise a polymetamorphic assemblage ranging from an early series of blastomylonite gneisses, schists, and layered migmatites of almandine amphibolite facies, to regionally retrograded cataclasite and mylonite zones, to narrow zones of massive breccia, shattered flinty crushrock, and graphitic gouge that attest to Laramide movement (McCallum, 1974).

A zone of mafic plutonic complexes and ortho-amphibolites trends northeastward across the Sierra Madre, Medicine Bow, and Laramie ranges, broadly coincident with the trend and position of the Mullen Creek-Nash Fork shear zone. Within this zone of mafic rocks, gold-bearing quartz veins and high-grade pockets of copper sulfides, and more rarely nickel and cobalt sulfides, have been mined locally, but these regions have not yet had major production from Precambrian ores.

Most base and precious metal mineralization in the central Medicine Bows consists of Au-Cu-bearing pyritic quartz-carbonate veins along southeast-trending tensional cross fractures and faults subsidiary to the Mullen Creek-Nash Fork shear zone. Mineralization (mostly as pyrite) also occurs sparsely within the major northeast-trending shear zones as small lenses and pods, apparently localized in dilatant zones.

Minor amounts of platinum metals have been found in the Centennial Ridge district (Hess, 1926) about eight miles northeast of the New Rambler mine. At Centennial Ridge, platinoids and gold are associated with sulfide or arsenide concentrations occurring as fracture and breccia fillings and lenses where branches of the Mullen Creek-Nash Fork shear zone and related faults cut mafic metaigneous and amphibolitic units (McCallum, 1968). No production of platinoid ore has been reported from this district. In the course of sampling mineralized localities in the central Medicine Bows, the writers have found high concentrations of platinum-group elements (from 1-2 ppm Pd + Pt to 40 ppm Pd and 30 ppm Pt) in copper sulfides and leached gossan material at two small vein occurrences adjacent to the Lake Owens Mafic Complex of Houston et al. (1968) six miles southeast of the New Rambler mine, near Albany, Wyoming.

Local lithologic units

Geologic relationships in the vicinity of the New Rambler mine are obscured by a thin veneer of upper Cenozoic boulder and gravel deposits. The principal exposures of bedrock units, all Precambrian, are in

prospect pits and mine workings. These units have been described by McCallum and Orback (1968).

The oldest rock type in the immediate vicinity of the mine is a mylonitic biotite-epidote-plagioclase gneiss that has undergone recurrent differential cataclasis. It is typically a light gray to pink, fine- to medium-grained gneiss composed of oligoclase-andesine, quartz, microcline, biotite, epidote, and chlorite.

Amphibolitized members of a large, layered tholeiitic intrusive complex, the Mullen Creek Mafic Complex of Houston et al. (1968) (Fig. 1), are prevalent in the mine vicinity. Most abundant are medium- to coarse-grained metadiorite and metagabbro consisting principally of plagioclase (variably sausseritized) and hornblende (commonly chloritized), although uralitized pyroxenes are locally significant, particularly in metagabbro. Common accessory minerals are magnetite, ilmenite, epidote, and biotite, accompanied by lesser amounts of sphene, allanite, apatite, and garnet. Coarse-grained metapyroxenite in the mine workings consists chiefly of hornblende, uralitized orthopyroxene and clinopyroxene, iron oxides, and pyrite, with accessory epidote, sphene, apatite, and, locally, olivine.

A few small diabasic dikes and sills, generally less than five feet in width, were mapped adjacent to the New Rambler deposit. The diabase is fine to medium grained and consists of nearly equal amounts of slightly altered calcic plagioclase and pyroxene. The relatively fresh condition of the diabase implies that it is younger than its amphibolitized neighbors.

An irregular granitic stock, about 1.5 square miles in outcrop area, is exposed a few hundred yards northeast of the New Rambler mine and was encountered in subsurface mine workings. Medium-grained equigranular pink granite comprises the bulk of this stock, although quartz monzonitic, aplitic, and pegmatitic facies are also present. Samples of granite collected from the mine dump are coarse grained and strongly epidotized. In order of decreasing abundance, the principal minerals of the granite are quartz, microcline, albite-oligoclase, biotite, and chlorite, and minor amounts of epidote, hornblende, muscovite, magnetite, and allanite. Lenses and sills of tourmaline-rich granite crop out on the northern margin of the stock. Albite, quartz, microcline, schorl, muscovite, and garnet are its major minerals.

All the preceding lithologic units have undergone variable degrees of cataclasis, recrystallization, and chemical reconstitution.

Local structure and general features of the New Rambler orebody

An east-trending branch of the Mullen Creek-Nash Fork shear zone is the dominant structural feature in the vicinity of the mine. The New Ram-

bler orebody was localized near the intersection of a poorly defined northeast-trending mylonite zone with this east-west mile-wide belt of intensely sheared rocks and a set of four close-spaced northwest-trending fractures (Fig. 1). The four small cross faults are not exposed at the surface, but old mine reports indicate that well-developed fault planes, dipping about 40 degrees to the northeast, were present at depth. Orback (1958) states that some copper mineralization and considerable fault gouge were encountered along these planes in the mine workings.

Inasmuch as the New Rambler mine workings are caved and inaccessible, and nearly all mine records were destroyed in a fire that terminated the mining operation in 1918, the following account of the geometry and structural control of the orebody is necessarily tenuous because it relies heavily on a few brief and sketchy reports published by early visitors to the active mine.

Kemp (1904) gives the most detailed description of the orebody, and the general outlines of his account are corroborated by subsequent reports. The mine's entire production¹ apparently came from three irregular pods of ore enclosed in decomposed metadiorite and metagabbro. Diamond drilling has shown that these units grade at shallow depth into "pyroxenite" and "peridotite," although the depths at which these transitions were encountered is highly erratic, due presumably to complex faulting (Kasteler and Frey, 1949).

The upper ore pod was described as a dome-shaped body extending from 30 to 70 feet below the ground surface and having a horizontal diameter of about 40 feet (Kemp, 1904, p. 248). The upper part of this body was a gossan of iron oxides from which the copper had been extensively leached. The lower part of the oxidized pod was heavily impregnated with copper carbonates, sulfates and oxides, chrysocolla, and native copper, with minor sulfides near the base.

About 50 feet southeast of the oxidized ore pod, a separate pocket of sulfide ore "of no definite outline" was encountered at a depth of 100 feet. This ore mass was about 25 feet high and extended 30 feet north-south and 50 feet east-west. A few tens of feet west of this pod, another large irregular ore shoot was opened up on the same level. Kemp (1904) reports that the part of the ore mass stoped out at that time was 40 feet north-south, 25 feet high, and 12 to 25 feet wide. He found it remarkable that "the usual vein minerals of the gangue, such as quartz, calcite, etc., are lacking. Instead we

have over an area of nearly a hundred feet east and west and the same distance north and south . . . the decomposition products of an eruptive dike [sic] in place" (p. 249). Actually, minor quartz is present, although the predominant gangue is gray to yellow cryptocrystalline jasperoid. The mafic rocks containing the ore are not "dikes" but are tectonically translated blocks and projections of the Mullen Creek layered mafic intrusive complex.

However, several tens of feet east of the three irregular ore pods, subsequent underground development encountered quartz-carbonate fissure veins related to the four small northwest-trending faults mentioned previously. A report by the U. S. Bureau of Mines (1942, p. 4) states that a map of the property, prepared in 1918 just prior to the fire, indicates that most of the underground development in the previous decade was on fissure veins. This development work was done on the assumption that the orebody was along fissures and that by following fissures other ore shoots might be found. Other than the three orebodies just discussed, no ore was disclosed by the rather extensive underground explorations. Bureau of Mines engineers (1942, p. 4) believed the ore to be "independent of fissure veins."

In summary, the disconnected reports on the New Rambler orebody suggest that it consisted of three large ore pockets of irregular outline. If the geometry of the stopes at the time of Kemp's (1904) visit can be taken as representing the distribution of ore in the deposit, the pods lacked a consistent trend. The ore was entirely in decomposed, sheared, mafic metaigneous rocks and was situated near the intersection of a northeast-trending mylonite zone and closely spaced northwest-trending faults with an east-trending branch of the Mullen Creek-Nash Fork shear zone. The nature of the affiliation, if any, between the orebodies and the cross faults is obscure; however, the intersecting shear zones may have generated zones of dilatancy in which ore deposition was localized.

Mineralization

Methods of investigation

Two hundred specimens of sulfide ore (variably oxidized) and altered metagabbroic host rock collected from the New Rambler mine dump were evaluated. Eighty-seven ore- and gangue-mineral separates and bulk samples of ore and host rocks were analyzed quantitatively for platinum-group elements and Au by a combined fire assay-emission spectrographic method described in detail by Cooley et al. (1976). Osmium cannot be determined by this method and was not sought. Ag and Cu in all 87 samples and Au, Ni, Co, Zn, As, and Te in some

¹ Approximately 6,000-7,000 tons of ore concentrates were shipped, but platinoids were extracted only from a small fraction, owing to belated recognition of their presence. Payment was received for 451 oz Pd and 170 oz Pt (U. S. Bureau of Mines, 1942).

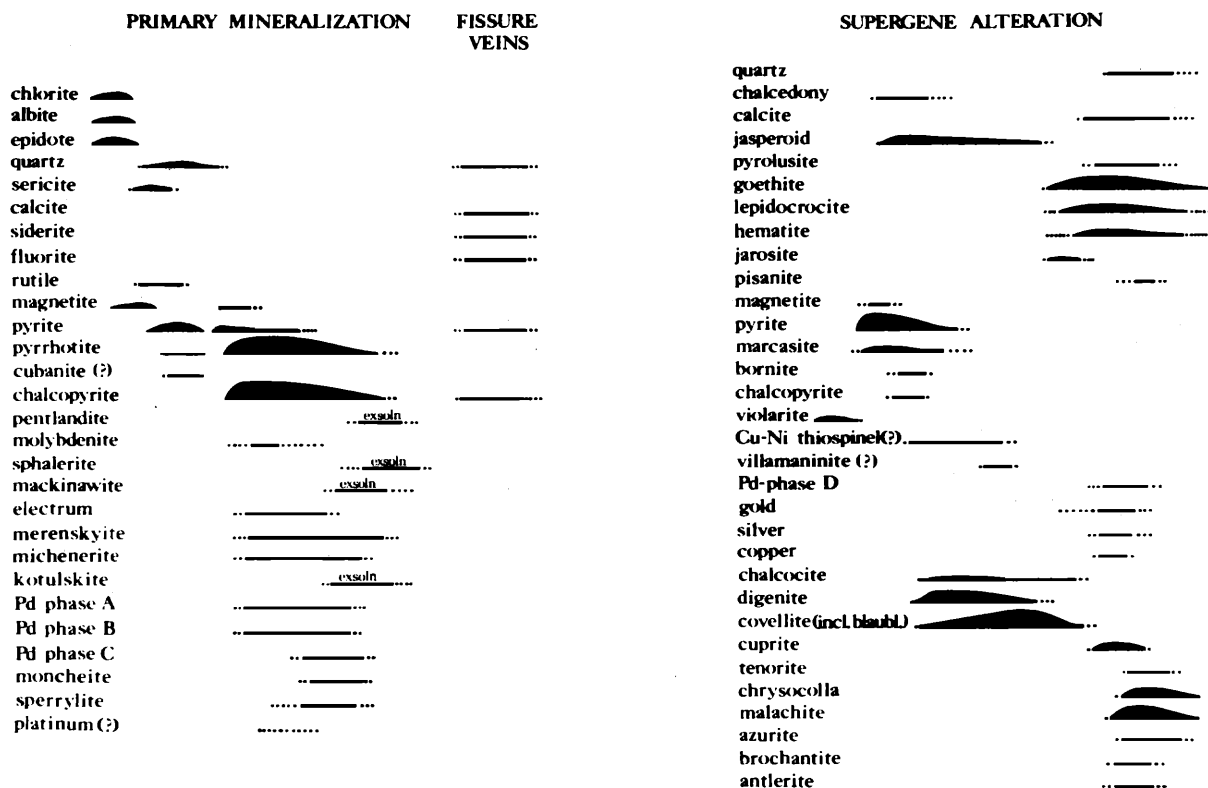


FIG. 2. Paragenetic sequence, New Rambler deposit. Queried minerals are those whose identities have not been verified unequivocally (platinum, Cu-Ni thiospinel?, villamaninite) or whose former presence is inferred ("cubanite"). "Cubanite" is intermediate solid solution of cubanite composition; "exsoln" is exsolution; and "incl. blaubl." following covellite means "including blaubleibender covellite."

specimens were determined by atomic absorption analysis. Other trace element characteristics of the 85 samples were determined by semiquantitative emission spectrographic analysis for 30 elements. One hundred twelve polished ore specimens and 14 thin sections of altered host rock were examined microscopically. Mineral identifications were made by optical means, X-ray powder diffraction analysis, and quantitative and semi-quantitative electron microprobe analysis. The paragenetic sequence outlined in Figure 2 is based on interpretation of ore and gangue mineral intergrowths.

Several minerals, principally those of the platinum-group elements, are unidentified and may represent new mineral species. Quantitative chemical, optical, and structural analyses of platinoid minerals and of two unusual Cu-Ni sulfide minerals are in progress.

Wall-rock alteration

Owing to poor bedrock exposure in the vicinity of the mine and to inaccessibility of the mine workings, most samples studied for effects of hydrothermal alteration were collected from the mine dump. Silicate rocks on the dump exhibit varying intensities

of silicification, sericitization, chloritization, and sausseritization.

Propylitic alteration: All rock units have been chloritized and sausseritized to a variable extent along the shear zones. Although greenschist-propylitic alteration has affected to some extent the country rocks over a broad area, development of the chlorite-epidote-clinzoisite-albite-magnetite (-pyrite) assemblage shows notable intensification with proximity to the orebodies. In most propylitized samples from the dump, the alteration is incomplete; much hornblende and lesser calcic plagioclase survive as corroded relics, and biotite is largely unaffected. Magnetite and epidote veinlets are abundant.

Quartz-sericite-pyrite: With further progress of wall-rock hydrolysis, relict plagioclase and albite are strongly replaced by sericite and quartz, and in turn the remaining hornblende, biotite, and chlorite are attacked. Pyrite is conspicuous as veinlets and disseminated grains, occasionally as overgrowths on magnetite. Reticulated nets of rutile platelets have developed along partings in decomposed hornblende. Minor amounts of glassy, fine- to coarse-grained quartz may express locally intense hydrothermal

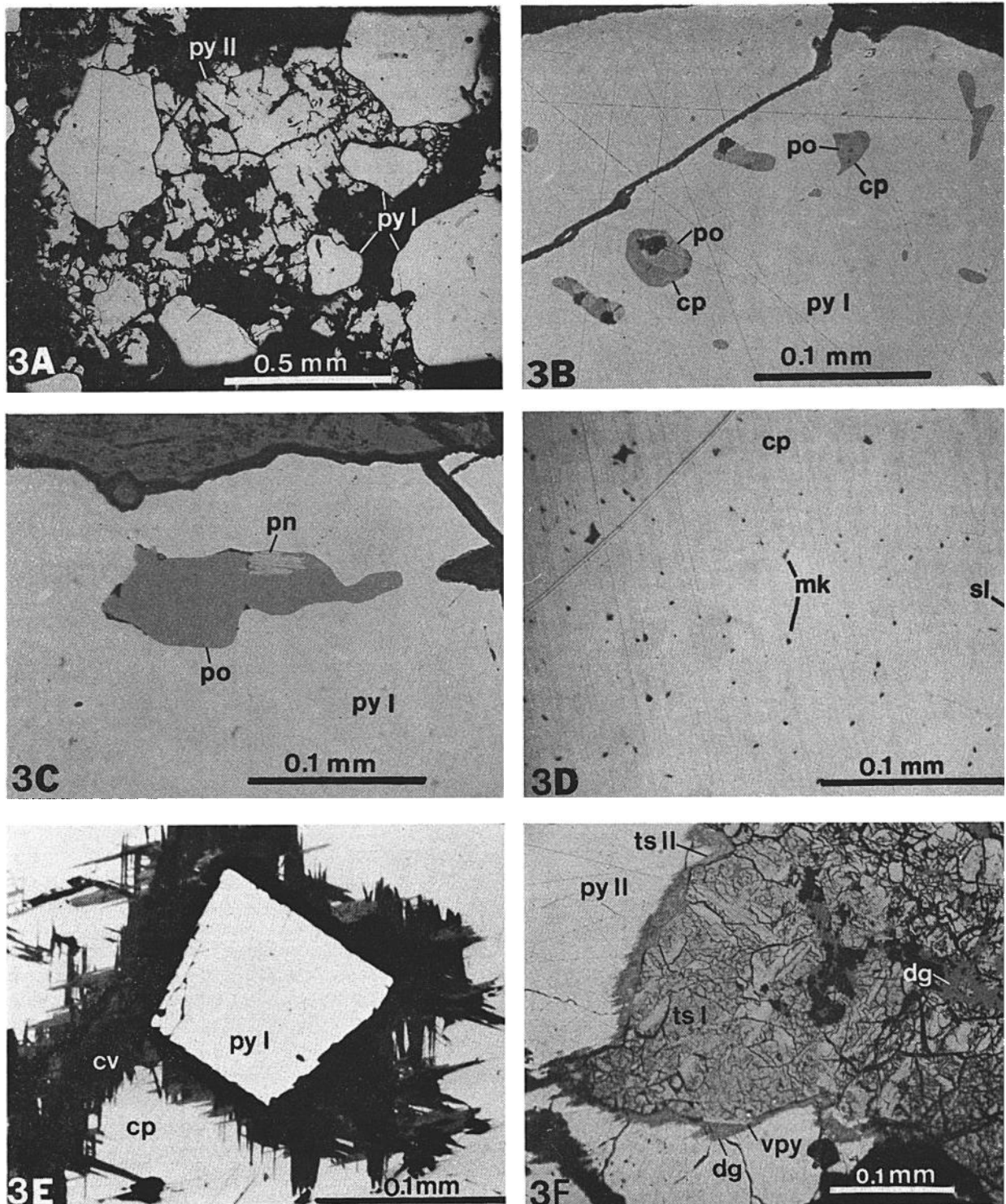


FIG. 3. A. Corrosively rounded and embayed grains of primary pyrite (py I) with incorporated small chalcopyrite-pyrrhotite and pyrrhotite-pentlandite blebs; the primary pyrite is intergrown with secondary pyrite (py II) that has replaced medium- to coarse-grained pyrrhotite. The rough appearance and traces of relict pyrrhotite {0001} parting distinguish supergene pyrite from hypogene pyrite. (Ore sample transitional between assemblages 1 and 2)

B. Chalcopyrite (cp) and pyrrhotite (po) as inclusions in primary pyrite (py I) of assemblage 1. Six of the inclusions shown are bimineralic.

silicification, but much of this material is difficult to distinguish from the products of pervasive supergene silicification discussed below. In addition to pyrite, sparse disseminations of chalcopyrite occur in quartz-sericite gangue, but in general it appears that zones of silicification and quartz-sericite alteration constitute nearly barren zones developed locally along the walls of fluid-bearing channels in the general vicinity of ore mineralization.

Jasperoid: With the exception of subordinate amounts of pyrite associated with quartz + sericite, the sulfide ore is enclosed in turbid microcrystalline or cryptocrystalline silica of supergene replacement origin, referred to in following discussions as jasperoid. Varieties of this secondary silica include massive microcrystalline quartz; large volumes of porous, crumbly, gray to white jasperoid composed of minute colloform silica grains and argillaceous-looking material shown by powder diffraction to be amorphous; dense, massive, slightly opaline translucent silica with a gel-like appearance; and masses of turbid, cryptocrystalline jasperoid that preserves with variable degrees of clarity the relict textural features of the original metagabbroic rock, viz., the granular fabric and relict cleavages of hornblende and chlorite. The latter type of jasperoid also typically contains nets and parallel sets of rutile prisms formerly disposed along cleavage planes of hornblende and biotite, and similar netlike arrays, sets of parallel platelets, and irregular wisps of sulfides that also were originally distributed along cleavages and grain boundaries of silicate minerals (notably hornblende) in the variably hydrolytically altered metagabbroic rocks

The presence of ferruginous and weakly copper-stained patches in some jasperoid and the gel-like appearance of much of it point to derivation by supergene decomposition of metagabbroic rocks enclosing the weathering ore masses under the influence of strongly acidic, H_2SO_4 -bearing meteoric solutions.

Early published reports indicate that all the ore occurred as huge "bunches" and streaks in "highly decomposed diorite [that] in its extreme form . . . is a white kaolinized mass of the consistency of soft clay but often retaining something of the original granular structure of the rock. Near the orebodies covellite grains are so uniformly distributed through

it as to give the appearance at a little distance of basic silicates in a white feldspathic rock" (Emmons, 1903, p. 97). No kaolin or other clay has been identified in this investigation, but much of the friable jasperoid fits that description. The account of abundant disseminated sulfides "near the orebodies" clearly implies that what was considered to constitute an orebody was essentially (or actually) massive sulfide. Ore specimens collected from the mine dump during this investigation are principally chunks of massive sulfide ore as much as a foot in diameter and irregular nodules of sulfide several inches across in a jasperoid (formerly metagabbro) matrix; less abundant are jasperoid disseminations in sulfide matrix (matrix ore) and jasperoid with granular disseminations of fine-grained ore minerals (disseminated ore).

Mineral associations in the ore

All available ore specimens exhibit some degree (usually intense) of supergene alteration. Published reports indicate that no fresh ore was mined. Ore specimens from the least oxidized portion of the alteration profile are affected by moderate to extensive replacement of primary ore minerals by supergene sulfides, by incipient limonitic oxidation, and by complete supergene silicification of the metagabbroic rock matrix. The least weathered examples of the various ore types provide the basis for this descriptive account. The mineralogy of the oxide zone, although interestingly varied, is for the most part peripheral to the focus of this report and is not discussed in detail. Because of total obliteration of some primary minerals by supergene processes, an account of the hypogene mineral assemblages necessarily must be interpretive in part. The sulfide ore can be classified into three distinct associations of primary ore minerals:

(1) An assemblage consisting principally of pyrite, with magnetite as a major accessory, and traces of chalcopyrite, pyrrhotite, and pentlandite, occurring as massive sulfide and as disseminations in the quartz-sericite wall-rock alteration facies;

(2) An association of chalcopyrite and pyrrhotite with minor pyrite and numerous trace accessories, including sphalerite, mackinawite, pentlandite, electrum, and five hypogene Pd and Pt minerals, oc-

C. Pentlandite (pn) as a feathery exsolution in pyrrhotite (po) enclosed by primary pyrite (py I) of assemblage 1.

D. Sphalerite stars (s1) and specks of mackinawite (mk) in chalcopyrite (cp) of assemblage 2.

E. Euhedral primary pyrite (py I) of assemblage 2 enclosed within chalcopyrite (cp). Covellite blades (cv) and void space have developed after chalcopyrite along the chalcopyrite-pyrite grain boundary.

F. Secondary pyrite (py II) partially encloses a subhedral grain of Cu-Ni thiospinel(?) after pentlandite (ts I). The fringe-textured phase around ts I is Cu-Ni thiospinel(?) after pyrrhotite (ts II). ts II shows preferential partial replacement by digenite (dg). Veinlet pyrite (vpy) occupies part of a shrinkage crack between ts I and ts II. (Assemblage 2)

curing as massive sulfide and as nodular and granular disseminations in metagabbroic rock;

(3) An association identical to (2) in major ore mineralogy and matrix material, but with a distinctive accessory base and precious mineral suite consisting of sphalerite, magnetite, pentlandite, electrum, and seven platinoid minerals.

Assemblage 1: About 5 percent of the ore collection belongs to this association. Medium-grained magnetite occurs abundantly in most specimens as euhedral to anhedral, corrosively rounded, extensively martitized and goethitized grains enclosed in nearly fresh pyrite. Semiquantitative emission spectrographic trace element analyses of magnetite separates reveal Mn contents in the 500 to 700 ppm range, and low contents of Cr (~ 20 ppm), Ti (less than 20 ppm), and V (~ 150 ppm).

Euhedral to anhedral pyrite, the principal sulfide in this assemblage, typically occurs as very coarse grained, polycrystalline massive sulfide and as disseminations in jasperoid and quartz-sericite matrix. The smooth polish and whiter brilliance distinguish this hypogene pyrite from the generally pitted, ragged, fine-grained, and slightly darker supergene pyrite that has replaced pyrrhotite of assemblages 2 and 3 (Fig. 3A). Spectrographic trace element analyses show that pyrite of assemblage 1 is relatively cobaltiferous (up to 3,000 ppm Co) and usually contains less than 1,500 ppm Ni, but disseminated pyrite contains up to 1 wt percent Ni, occurring mainly as inclusions of nickeliferous pyrrhotite + pentlandite.

An interesting feature of this assemblage is the occurrence within pyrite of tiny inclusions (typically 10–50 microns across) of pyrrhotite and chalcopyrite, mostly as visibly composite ovoid blebs (Fig. 3B). These are locally so abundant as to constitute an emulsion in pyrite. Pentlandite (Fig. 3C), identified by microprobe analysis, is recognized in fewer than 1 percent of the inclusions (principally the largest ones), sometimes in clearly trimineralic blebs.

Assemblage 2: This mineral association is common to about 80 percent of the ore samples collected. All samples have been strongly affected by supergene processes and consist principally of chalcopyrite, pyrite, covellite, and goethitic limonite. Most specimens are devoid of gangue, but in some larger samples, ore minerals occur as fist-size and smaller corroded sulfide nodules in jasperoid matrix and in some cases as granular disseminations in silica.

Chalcopyrite was the most abundant sulfide in primary ore. Coarse to very coarse, complexly twinned chalcopyrite contains a variety of other minerals as inclusions. Sparse small globules of pyrrhotite in chalcopyrite are conspicuous in some samples of nodular and massive ore. Mackinawite occurs, com-

monly in profusion, as exsolved, minute, discontinuous lamellae and crystallographically oriented specks. Sphalerite is present in chalcopyrite as tiny stars (Fig. 3D), isolated blebs and rods, and discontinuous lamellae. The coalescence of rods to form discontinuous lamellae manifests control by octahedral planes of the chalcopyrite structure and suggests that these minute sphalerite inclusions have originated by exsolution from chalcopyrite. Larger, equant sphalerite grains (up to 0.1 mm across) of apparent nonexsolution origin are very rare.

Spectrographic trace element analyses of chalcopyrite of assemblage 2 show Zn contents typically in the range 1,000 to 1,500 ppm. Zn contents of other major sulfide minerals are low. Statistical analysis of the associations of metallic trace and major elements in massive sulfide ore reveals a high correlation coefficient between Cu and Zn—0.786 at the .001 significance level—indicating that chalcopyrite contains virtually all the zinc in the deposit, principally as exsolved sphalerite inclusions.

Chalcopyrite usually shows variable degrees of replacement by a grid of tapering covellite lamellae, in part of the *blaubleibender* (blue-remaining) variety; digenite and, more rarely, chalcocite replace chalcopyrite of assemblage 2 in some disseminated ore.

Another supergene metasome of chalcopyrite in this suite occurs sparsely in most samples (abundantly in a few) as tiny, bronze-pink, isotropic cubes, aggregates of cubes, and anhedral grains always enclosed in covellite and commonly as rim overgrowths on tiny (5–15 microns) granules and rods of secondary pyrite that in part is derived from replacement of mackinawite. Preliminary electron microprobe analysis shows the bronze-pink mineral to be a sulfide of Cu, Ni, and Co, in that order of abundance, having a metal:sulfur ratio closely approximating 1:2. It is tentatively identified as *villamaninite*, $(\text{Cu, Ni, Co})\text{S}_2$, a rare mineral with pyrite structure. More comprehensive data regarding the peculiar mineralogy of nickel in the New Rambler deposit are reserved for publication in a later report.

The massive sulfide ore contains hypogene pyrite as a minor accessory disseminated in chalcopyrite (Fig. 3E). The primary pyrite occurs as small cubes, usually 50 to 150 microns across, that are distinctly whiter than secondary pyrite of the same assemblage, owing probably to the effects of dissimilar Co and Ni contents in the two varieties.

Most secondary pyrite of this suite has a pitted and rather ragged appearance (Fig. 3A). It occurs typically as large, compact, granular masses of fine to very fine pyrite with or without intergrown marcasite. Granoblastic masses of pyrite and marcasite often display conspicuously the inherited relict basal

parting of medium- to coarse-grained pyrrhotite and contain sparse, tiny, ragged inclusions of relict pyrrhotite. The granoblastic masses of secondary pyrite and marcasite usually also contain disseminations (sometimes emulsions) of cogenetic minute magnetite granules, most of which do not exceed 5 microns in diameter. Also typical of supergene pyrrhotite replacement is the occurrence of extremely fine grained "melinkovite" pyrite and marcasite as porous, sandy-looking, sieve-textured masses disposed in large concentric shells and making up the walls of coarse, cellular boxworks

In summary, pyrrhotite was originally a major primary mineral that, together with chalcopyrite, constituted the bulk of assemblage 2 ore. Pyrrhotite has survived only as sparse minute shreds in secondary iron disulfides and as small globules armored by chalcopyrite.

Spectrographic trace element analyses of secondary pyrite (ex-pyrrhotite) separates from assemblage 2 ore have a relatively Ni-rich, Co-poor chemical signature (Ni greater than 5,000 ppm, Co less than 700 ppm) distinct from that cited for primary pyrite of assemblage 1. Quantitative electron microprobe analysis shows that the Ni content of secondary pyrite is inhomogeneously distributed, commonly ranging from less than 0.5 to more than 2 wt percent within a 2-mm² area of fine-grained pyrite. Watmuff (1974, p. 206–208) has documented similar contrasts in Ni and Co contents of hypogene and supergene pyrite in a study of the weathered profile at the Mt. Windarra nickel deposit, Western Australia.

A most interesting mineralogical feature of some samples of disseminated sulfide ore is a pale, gray-white, optically isotropic mineral enclosed in and scattered along the margins of granoblastic secondary pyrite-marcasite masses. This mineral (Fig. 3F) comprises up to about 2 modal percent of some specimens. Preliminary electron microprobe analysis of several points within a single homogeneous grain of this mineral shows it to be a sulfide of Cu, Ni, Fe, and Co, in that order of abundance, yielding a stoichiometry very near (Cu, Ni, Fe, Co)₃S₄. The stoichiometry and optical and textural characteristics of this phase suggest that it may be a thiospinel.

The disposition of the Cu-Ni thiospinel(?) in secondary pyrite as flames parallel to relict pyrrhotite cleavage and as grains clustered along the margins of former pyrrhotite grains is texturally reminiscent of pentlandite-pyrrhotite intergrowths in ores of some other deposits. In a discussion of supergene alteration of the Mt. Windarra nickel sulfide deposit, Watmuff (1974) describes textural features of the replacement of pentlandite by violarite that are identical to textural features of the Cu-Ni thiospinel(?)

in New Rambler ore. Watmuff reports (p. 212) that violarite shows increasing enrichment in copper toward the top of the secondary enrichment zone, although his data indicate that Cu contents of violarite do not exceed 5 to 6 wt percent in that relatively Cu poor, Ni rich deposit. In view of the strong textural resemblance to typical pyrrhotite-pentlandite intergrowths and the close similarity to textural features developed during violaritization of pentlandite, as described by Watmuff (1974), it is concluded that the Cu-Ni thiospinel(?) originated from pentlandite, possibly via alteration of normal violarite or by direct replacement of pentlandite. Pyrrhotite of the same samples is directly replaced by supergene Cu sulfides as well as by pyrite and marcasite and a narrow fringe of Cu-Ni thiospinel(?) along former pyrrhotite-pentlandite grain contacts (Fig. 3F).

Identifications of platinum and palladium minerals have been made on the basis of optical properties and quantitative electron microprobe analyses. Several Pd minerals remain unidentified and are suspected to constitute new mineral species. Quantitative determinations of the compositional, structural, and optical characteristics of the platinoid minerals are in progress. The results of these investigations and an account of the analytical procedures will be presented in a separate report dealing with the platinoid mineralogy of the New Rambler deposit.

The hypogene platinoid mineral suite of assemblage 2 consists of rhodian sperrylite [(Pt, Rh)As₂], merenskyite [(Pd, Pt)(Te, Bi)₂], kotulskite [Pd(Te, Bi, Sb)], michenerite [(Pd, Pt)(Bi, Sb)Te], and an unidentified cream-colored, weakly anisotropic mineral of composition PdTe₂ that occurs as discrete grains intergrown with bismuthian merenskyite. The PdTe₂ mineral is provisionally referred to as Pd phase C. In addition, a light coffee-brown, extremely anisotropic Pd-Bi-Te mineral of indeterminate stoichiometry occurs as thin rims replacing michenerite (and rarely merenskyite) in weakly oxidized ore. This supergene Pd mineral is here referred to as Pd phase D (Fig. 4A).

The most abundant of these species is merenskyite. In polished section, it almost invariably appears intergrown with subordinate but variable amounts of kotulskite. The latter commonly occurs as discontinuous lamellae oriented parallel to the excellent {0001} cleavage of merenskyite. The manner of this intergrowth is clearly indicative of kotulskite exsolution from a merenskyite host. Irregular corrugation lamellae of kotulskite in merenskyite (Fig. 4B) and kotulskite partial rims on merenskyite are also interpreted as derived by exsolution. An experimental investigation of phase relations in the Pd-Bi-Te system by Hoffman and MacLean (1976) has established that between 575° ± 10°C and 710° ±

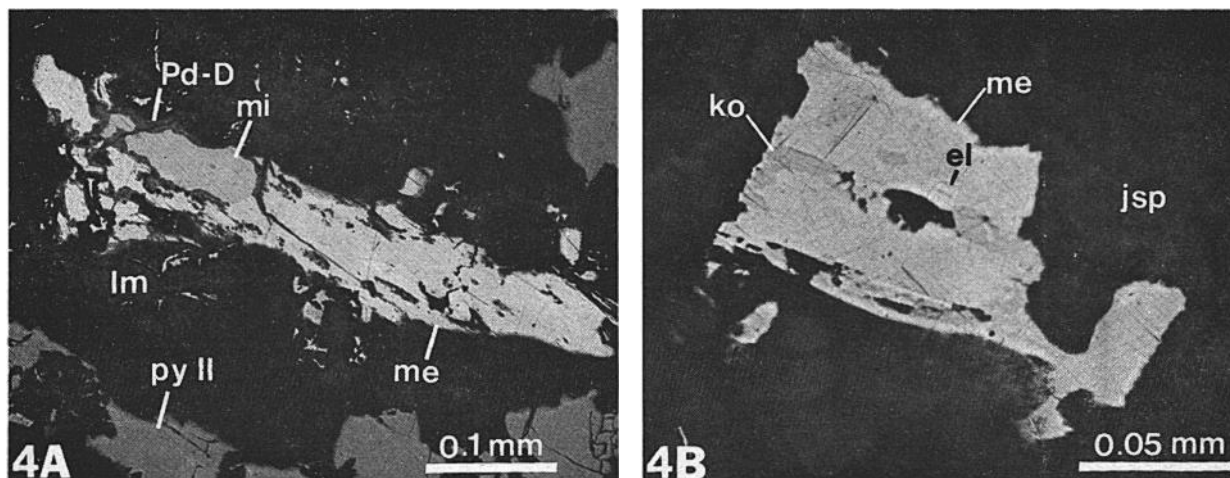


FIG. 4. A. Merenskyite (me) intergrown with michenerite (mi). Michenerite has a dark rim of supergene Pd phase D. The corroded palladium minerals are surrounded by void space and limonite (lm) developed by oxidation of secondary pyrite (py II). (Assemblage 2)
 B. Merenskyite (me) with patchy intergrowths of darker kotulskite (ko). Merenskyite encloses a grain of electrum (el). The matrix is supergene jasperoid (jsp) that has replaced metagabbroic matrix. (Assemblage 2)

$10 \pm ^\circ\text{C}$, solid solution between merenskyite and kotulskite is complete. The extent of the solid-solution field at lower temperatures has not been defined. Michenerite is a frequent associate of merenskyite, the two occurring as granular intergrowths suggestive of independent penecontemporaneous deposition (Fig 4A). Pd phase C (PdTe_2) has been encountered in two ore specimens as granular intergrowths with merenskyite.

The palladium minerals occur as anhedral grains, usually 75 to 250 microns across, but occasionally exceeding 600 microns, enclosed in chalcopyrite or its derivative covellite and limonite, in secondary pyrite-marcasite-limonite masses (ex-pyrrhotite), and in supergene silica that replaced metagabbroic silicates. As many as 15 aggregates of merenskyite-kotulskite-michenerite have been encountered in a single polished surface of less than 2 cm diameter. No palladium minerals have been seen in strongly oxidized ore from upper levels of the weathered zone. Of the eight sperrylite grains encountered in 97 polished sections of sulfide ore examined, three grains occur with assemblage 2—one intergrown complexly with merenskyite in massive sulfide ore, one as a partial rim on michenerite in metasomatic jasperoid, and another also in disseminated sulfide ore as an isolated grain in weathered metagabbroic matrix.

Electrum is a rare trace accessory in assemblage 2. The electrum occurs as small grains, 10 to 100 microns across, enclosed in jasperoid, merenskyite (Fig. 4B), and sulfides.

Textures of assemblage 2 ore mineral intergrowths suggest penecontemporaneous deposition of pyrite,

pyrrhotite (or locally, Fe-Ni monosulfide solid solution—mss), chalcopyrite ss, electrum, michenerite, merenskyite ss, Pd phase C, and sperrylite, followed at lower temperatures by exsolution of kotulskite from merenskyite ss, of mackinawite and sphalerite from chalcopyrite ss, and, in disseminated and matrix ores, of pentlandite from mss (Fig. 2).

Some assemblage 2 ore is cataclastic and is veined by supergene pyrite, marcasite, and silica, but there is no evidence of primary sulfide recrystallization or hydrothermal neomineralization, the lack of which suggests that the cataclastic effects may be relatively young—Laramide or Tertiary.

Assemblage 3: Samples belonging to this suite comprise about 15 percent of the ore collection. Although the major mineralogy of this assemblage is identical to that of assemblage 2, the accessory minerals, textural features, and weathering characteristics are distinctive.

Chalcopyrite shows extremely complex twinning. It is devoid of exsolved mackinawite, but sphalerite inclusions are as abundant as in assemblage 2, occurring in chalcopyrite as isolated tiny rods typically consistent in crystallographic orientation. Slightly larger equant grains of primary (nonexsolved) sphalerite are very rare. In addition, chalcopyrite of this suite typically contains pentlandite and violarite as sparsely scattered specks, delicate filamentous bodies and lamellae (oriented parallel to sphalerite rods), few of which exceed 75 microns in length. Large particles of violarite contain oriented shrinkage cracks typical of violarite derived by supergene alteration of pentlandite. The lamellar and delicate filamentous, wispy forms of some of these minerals

bodies suggest that the pentlandite originated, at least in part, by exsolution from chalcopyrite. Cu-Ni thiospinel(?) was encountered rarely in assemblage 3 disseminated ore.

Other accessory minerals of assemblage 3 are magnetite as fresh to slightly martitized euhedral grains and primary pyrite as rare small euhedral to anhedral grains in chalcopyrite.

Secondary pyrite and marcasite with textural characteristics similar to those discussed previously for assemblage 2 are major constituents of assemblage 3. In many samples of this ore type, pyrro-

tite has been replaced not only by marcasite and pyrite but by a variety of supergene Cu sulfides as well, including covellite, digenite, bornite, and chalcopyrite. These occur mostly as very fine grained, porous, concentrically shelled, polymineralic masses. Chalcocite, sparse in assemblage 2, is the most common supergene metasome of chalcopyrite in assemblage 3.

Native silver is commonly visible in partially oxidized samples of assemblage 3. It occurs as fine flakes dispersed sparsely through moderately or poorly crystallized limonite and as larger grains en-

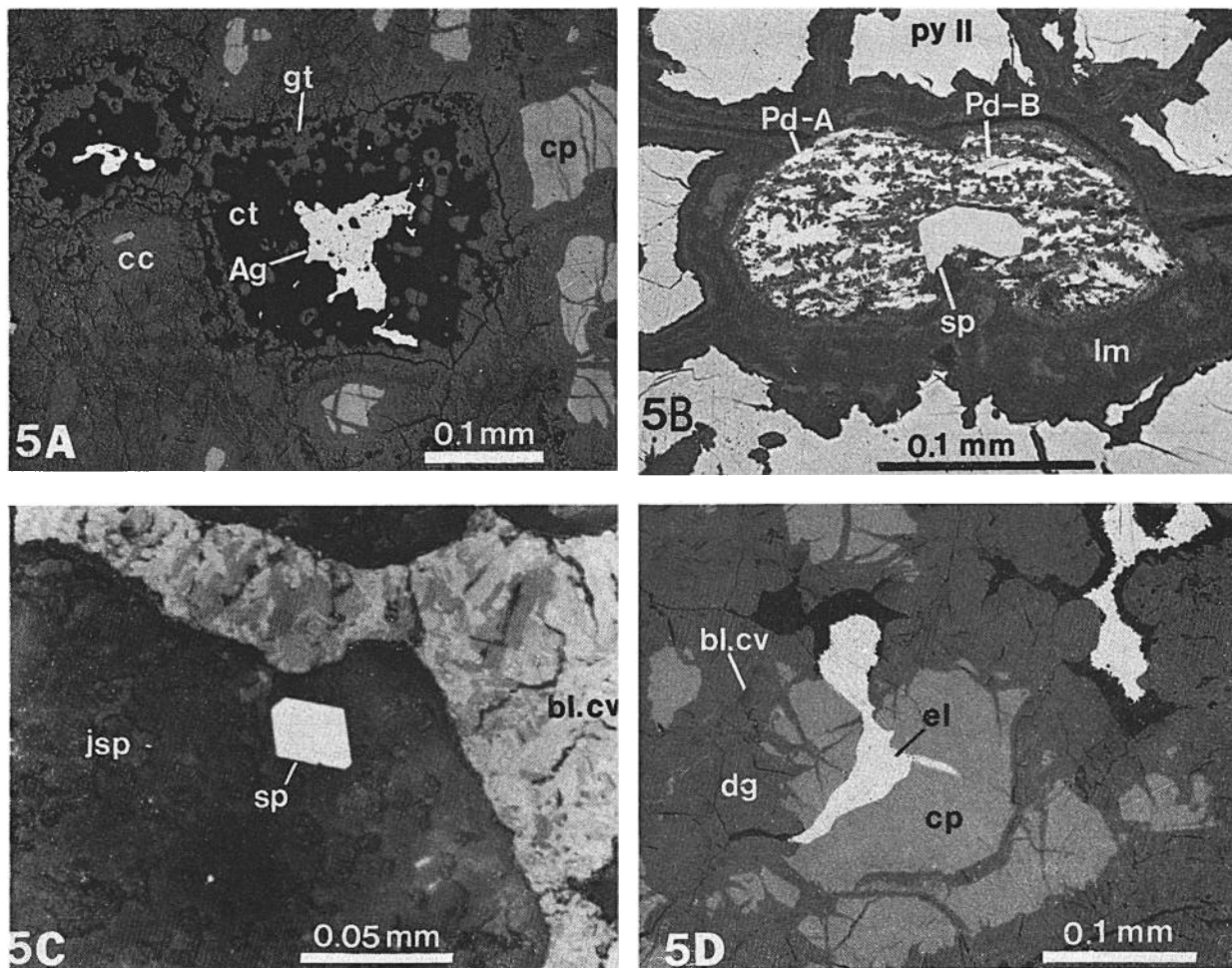


FIG. 5. A. Supergene native silver that, together with supergene calcite (ct), occupies a solution cavity in oxidized ore of assemblage 3. Associated minerals are chalcopyrite (cp), chalcocite (cc), and colloform and massive goethite (gt).

B. Pd phase A encloses a subhedral grain of sperrylite (sp) and a small, darker grain of Pd phase B. Pd phase A is mottled by a dark, Pd-bearing, compositionally inhomogeneous material of supergene alteration origin. Limonite (lm) partially replaces secondary pyrite (py II) after pyrrohotite. (Assemblage 3)

C. Sperrylite (sp) as a characteristically well-developed crystal enclosed in supergene jasperoid (jsp). Blaubleibender covellite (bl. cv.) after chalcopyrite is conspicuous. (Assemblage 3)

D. Electrum (el) intergrown with chalcopyrite (cp) that is strongly replaced by digenite (dg) and blaubleibender covellite (bl. cv.). Black areas adjacent to electrum are solution cavities. (Assemblage 3)

closed in secondary calcite in supergene solution cavities (Fig. 5A). Microprobe scans of native silver show a small arsenic content but no trace of platinum-group elements, Au, or other metals.

The only hypogene silver mineral recognized in New Rambler ore is silver-poor electrum, which is far less abundant in assemblage 3 than native silver. Probably most of the Ag from which supergene native silver formed was liberated from solid solution in the weathering of chalcopyrite. The average Ag content of chalcopyrite, as determined by atomic absorption analyses of five chalcopyrite separates, is 62 ppm. Tests of Ag correlations with other elements in chalcopyrite—secondary pyrite ore yield the strongest correlation coefficient with Cu ($r_s[\text{Ag-Cu}] = 0.668$), indicating that chalcopyrite carried most of the Ag in primary ore.

Two platinum and five palladium minerals constitute the platinoid mineral assemblage of this ore type. Michenerite, merenskyite, and kotulskite, the most common Pd minerals in assemblage 2, are relatively rare in this association. By far the predominant platinoid mineral in assemblage 3 is a pale apricot-yellow, moderately anisotropic mineral corresponding closely to the formula $\text{Pd}_5(\text{Bi, Sb})_2\text{Te}_4$. This unidentified mineral is provisionally termed Pd phase A (Fig. 5B). It occurs as small anhedral grains, typically 50 to 250 microns across, enclosed in chalcopyrite and supergene replacements of chalcopyrite and pyrrhotite.

Some of Pd phase A contains tiny inclusions of a slightly darker, peach-buff-colored Pd-Te-Bi-Sb mineral, referred to as Pd phase B (Fig. 5B). This mineral conforms exactly to the stoichiometry $\text{Pd}_5(\text{Te, Bi, Sb})_2$.

Pd phase A generally shows supergene alteration of variable degree to a dull gray-brown substance (the darker mottling material in Fig. 5B) that qualitative microprobe examination shows to be an inhomogeneous, compositionally complex material containing appreciable Pd, Bi, and Te, but also much Cu and Fe. Microscopic inspection suggests that the alteration material is either amorphous or a mixture of several minerals with grain size below the limits of optical resolution.

Sperrylite occurs enclosed in Pd phase A (Fig. 5B) and more commonly as discrete euhedra disseminated in jasperoid (Fig. 5C). In one unusually Pt rich, relatively Pd poor sample of disseminated ore, moncheite $[(\text{Pt, Pd})(\text{Te, Bi})_2]$ has been encountered as granular intergrowths with slightly platinian michenerite.

Electrum is seen more frequently in assemblage 3 than in assemblage 2, usually enclosed in chalcopyrite or its Cu sulfide replacements (Fig. 5D). The mean Au content of 7 analyzed bulk ore samples of

assemblage 3 is 10 ppm; the mean Au content of 13 bulk samples of assemblage 2 ore is 1 ppm, as determined by combined assay-emission spectrographic analysis. Microprobe analysis of one electrum grain (shown in Fig. 5D) yielded an Ag content of 28.2 wt percent and no detectable platinum-group elements.

The sequence of deposition of hypogene minerals of assemblage 3 appears to be (1) magnetite and pyrite; (2) chalcopyrite ss, pyrrhotite or mss, electrum, sperrylite, moncheite, merenskyite ss, michenerite, and Pd phases A and B; and (3) exsolution of pentlandite from mss, of sphalerite and pentlandite from chalcopyrite ss, and of kotulskite from merenskyite ss. The available specimens of this assemblage have not been affected by cataclasis. The non-cataclastic state and the distinctive accessory mineral suite and weathering characteristics of assemblage 3 ore suggest that it may have come from a different ore shoot than assemblage 2.

A single, perfect octahedral crystal of a weakly ferromagnetic, metallic white mineral tentatively identified as Pt-Fe alloy was obtained (along with 12 sperrylite grains and a trace of Au) by multistage acid digestion of 600 grams of Pt-rich (20 ppm Pt) cuprite-malachite-limonite ore. Although the Pt-Fe alloy is presumed to be a relict hypogene mineral, its paragenetic affiliations in unoxidized ore are not known.

A few tiny flakes of molybdenite, identified by X-ray powder diffraction analysis, also occur in otherwise totally oxidized ore. Most ore samples analyzed contain less than 20 ppm Mo (100 ppm maximum).

Quartz-carbonate fissure veins: Several tens of feet east of the ore pods, fissure veins were encountered in the mine workings. Material from the fissure veins collected on the mine dump consists principally of milky quartz (mostly massive but some with crystal druses), abundant calcite and siderite, traces of purple fluorite, and limonite probably derived from pyrite. A report by the U. S. Bureau of Mines (1942) states that little ore was encountered along fissure veins. The relation of the fissure veins to the main mineralization event is unresolved.

Temperatures of Ore Deposition

Most standard geothermometry techniques are inapplicable to New Rambler ore because of the complex ore history. Hydrothermal quartz is unsuitable for fluid inclusion studies, owing to very fine grain size or cataclastic effects. Pervasive weathering effects preclude the application of sulfur-isotope thermometry. However, applications of thermochemical data on conditions of ore-mineral compatibilities permit meaningful inferences to be drawn

regarding the general range of temperatures of ore deposition in this deposit.

Of particular interest in this regard are the bimineralic pyrrhotite-chalcopyrite inclusions in primary pyrite of assemblage 1 (Fig. 3B).² Pyrrhotite is about as abundant in the inclusions as chalcopyrite. The fact that the majority of the inclusions are visibly composite implies that most of the remainder are also bimineralic in the third dimension, which strongly suggests that the chalcopyrite and pyrrhotite in these inclusions are the disproportionation products of a once-homogeneous phase poikilistically included in the pyrite. Heating experiments were not applicable to New Rambler ore samples, owing to the prevalence of limonitic oxidation of pyrrhotite in these inclusions (black spots in Fig. 3B). However, in heating experiments conducted by Won Park (pers. commun., 1975) of Kennecott Corporation on similar chalcopyrite-pyrrhotite blebs in hydrothermal pyrite, the chalcopyrite + pyrrhotite homogenized near 325°C.

Examination of phase stability diagrams for the Cu-Fe-S system (Yund and Kullerud, 1966; Craig and Scott, 1974; Sugaki et al., 1975) at temperatures below 500°C (as required by the wall-rock alteration mineral assemblages) reveals that the only phase that coexists stably with pyrite and is compositionally intermediate between chalcopyrite and pyrrhotite is the cubic intermediate solid solution (iss) phase present in the central portion of the system Cu-Fe-S at intermediate to high temperatures. Experimental studies by Yund and Kullerud (1966) and Kullerud et al. (1969) have shown that at temperatures from 743° to 334°C pyrite coexists stably with cubic iss of composition very near that of cubanite. The tie line between these two phases precludes stable coexistence of pyrrhotite and chalcopyrite compositions in the 743° to 334°C temperature interval. At 334° ± 15°C the tie line between pyrite and cubic iss of cubanite composition is broken, and chalcopyrite + pyrrhotite becomes a stable assemblage (Yund and Kullerud, 1966, p. 476). Additional, although inconclusive, data presented by Yund and Kullerud (1966, p. 476) place this tie-line change at 328° ± 5°C.

Therefore, if the bimineralic inclusions in pyrite of assemblage 1 are the disproportionation products of a homogeneous phase, as indicated by results of heating experiments cited above, then cubic iss of cubanite composition is the only reasonable parental candidate. (Orthorhombic cubanite exists stably only at temperatures below 200°–215°C, Cabri et al.,

1973.) These inferences require that: (1) sulfide assemblage 1, consisting of magnetite (relict) + pyrite + mss + iss of cubanite composition, was deposited at temperatures above ~334°C; (2) the iss inclusions in pyrite disproportionated to chalcopyrite + pyrrhotite at or below that temperature; (3) the medium- to coarse-grained chalcopyrite-pyrrhotite (-pyrite-platinoid) ore of assemblages 2 and 3 was deposited below ~334°C.

The strong corrosional rounding and embayment of assemblage 1 pyrite (with abundant bimineralic inclusions) enclosed by secondary pyrite (ex-pyrrhotite) in an ore sample mineralogically transitional between assemblages 1 and 2 (Fig. 3A) can be accounted for by one of two hypotheses: (1) an interval of sulfide dissolution intervened between deposition of the highly pyritic sulfide assemblage 1 and the chalcopyrite-pyrrhotite ore of younger assemblages; or (2) the corrosion of the pyrite is due to solid-state reactions following sulfide deposition.

The likelihood of the latter alternative is supported by considerations regarding distribution of accessory hypogene pyrite of a later generation (without inclusions) in typical ore of assemblage 2. Small, euhedral pyrite grains are present, enclosed in chalcopyrite of assemblage 2 (Fig. 3E) in amounts commonly exceeding 1 modal percent, but a determined search failed to disclose any hypogene pyrite grains in secondary pyrite (ex-pyrrhotite) of this assemblage. Hypogene and supergene pyrite are easily distinguishable where seen in contact in the association transitional between assemblages 1 and 2 (Fig. 3A). Mutual inclusion and intergrowth relationships indicate that chalcopyrite and pyrrhotite of assemblage 2 are paragenetically contemporaneous. It is suspected that pyrite cubes such as that shown in Figure 3E enclosed in chalcopyrite were initially enclosed within paragenetically contemporaneous pyrrhotite as well, but that they were resorbed (at least beyond recognition, if not entirely) by pyrrhotite upon transformation from a hexagonal to a monoclinic structure.

With decreasing temperature, the composition of hexagonal pyrrhotite in equilibrium with pyrite assumes increasingly iron-rich, sulfur-poor compositions, reaching a maximum Fe:S ratio near the temperature of the hexagonal-monoclinic transformation (see Craig and Scott, 1974, for a summary of data pertaining to the pyrite-pyrrhotite solvus). The composition of monoclinic pyrrhotite in equilibrium with pyrite is more sulfur rich, and on transformation from hexagonal to monoclinic structure, pyrrhotite may adjust its composition by reaction with pyrite (Kullerud et al., 1969, p. 357). These authors suggest that this reaction may be responsible for corrosion of pyrite associated with monoclinic pyr-

² A few larger pyrrhotite inclusions containing pentlandite, usually without associated chalcopyrite (Fig. 3C), apparently represent traces of mss included poikilistically in the pyrite as a coprecipitated phase.

rhotite in Sudbury ores. The temperatures of the hexagonal-monoclinic transformation has been subject to considerable uncertainty, but Taylor (1969) found that this transformation was reversible at $292^{\circ} \pm 4^{\circ}\text{C}$ for pyrrhotite of composition Fe_7S_8 , and Sugaki et al. (1975) have synthesized monoclinic pyrrhotite coexisting with pyrite at 300°C in hydrothermal experiments believed by them to represent equilibrium conditions. These lines of evidence suggest that pyrrhotite in massive sulfide ore of assemblage 2 was probably deposited as hexagonal pyrrhotite at temperatures between $\sim 300^{\circ}$ and $\sim 334^{\circ}\text{C}$. (Similar considerations should apply to sulfide assemblage 3 as well, but oxidation of pyrite in that assemblage has destroyed most of the evidence for this argument.) Primary pyrite is apparently absent from Cu-Ni thiospinel(?)-(ex-pentlandite)-bearing specimens of disseminated ore, and chalcopyrite of this association is markedly impoverished in sphalerite and particularly in mackinawite exsolution bodies. These features suggest dwindling deposition of pyrite with diminishing temperature.

In conclusion, thermochemical data applicable to the mineral association magnetite (relict) + pyrite + mss + iss of cubanite composition in assemblage 1 indicate development of this assemblage at temperatures somewhat (but probably not far) above $\sim 334^{\circ}\text{C}$; similar considerations require that the hypogene assemblage chalcopyrite ss + Ni-bearing pyrrhotite + accessory pyrite + platinoid minerals of assemblages 2 and 3 were deposited below $\sim 334^{\circ}\text{C}$, but probably above $\sim 300^{\circ}\text{C}$. Disseminated and matrix ore of assemblages 2 and 3 (mss + chalcopyrite ss + accessory platinoid minerals) may have been deposited within or below this $\sim 334^{\circ}$ to 300°C temperature interval. Naldrett et al. (1967) showed that at temperatures as low as 300°C pyrrhotite readily accepts in excess of 15 wt percent Ni into solid solution; Ewers (1972, p. 24) has demonstrated that nickel is taken up by pyrrhotite at temperatures above 200°C . Thus, initial Ni contents of 3 to 5 wt percent in mss of some ore samples cannot be taken as an indication of relatively high deposition temperature.

Considerations Regarding Genesis of the New Rambler Deposit

Two hypotheses regarding formation of the deposit deserve consideration: (1) The deposit is solely the product of hydrothermal processes. The metal content of the deposit has been derived by hydrothermal leaching of a large volume of cataclastic mafic rock where part of the Mullen Creek Mafic Complex is intensely sheared along an east-west belt nearly a mile wide. The ore was deposited as fissure filling and metasomatic

replacement of mafic rock within dilatant zones or other similarly favorable loci at the intersection of the east-west shear zone with a subsidiary northeast-trending mylonite zone. Northwest-trending cross faults adjacent to the deposit do not seem to have been the main conduits for introduction of metals. (2) The orebody represents portions of a magmatic sulfide deposit tectonically translated into their present positions in the shear zone and hydrothermally reworked by fluids introduced along avenues in the shear zone or cross faults.

Evidence for an exclusively hydrothermal genetic process

Lines of evidence supporting a strictly hydrothermal origin for the deposit include the structural setting, the general spatial coincidence of ore and hydrothermal alteration, textures of ore and silicate matrix intergrowths, and, most significantly, the predominance of the more readily soluble platinum-group elements, Pd and Pt, and the relative unimportance of the more chemically refractory platinoids Ir, Os, Ru, and Rh.

Ore textures: No textural evidence of magmatic origin of the sulfides has been recognized, e.g., sulfides as rounded or droplet forms in silicate matrix or sulfides as interstitial granular intergrowths with magmatic silicates. Rather, sulfides and magnetite occur as fracture fillings and fine granular dispersions within silicate grains, as invasions along grain boundaries and cleavages of silicate minerals (notably hornblende), and as angular, polycrystalline sulfide aggregates whose regular granular-textured distribution in metasomatic supergene jasperoid suggests preferential replacement of certain (unrecognizable) minerals of the metagabbroic rock. Because hornblende is easily recognized as a mineral strongly affected by ore-mineral replacements, it is apparent that sulfide crystallization followed (possibly closely) the diaphoresis to epidote-amphibolite (and locally lower) grade of the gabbroic host and other rocks throughout the district during the period of major cataclastic activity along the Mullen Creek-Nash Fork shear zone.

Hydrothermal alteration: The distribution of ore in the deposit correlated rather closely with the volume of mafic rock affected by intensified hydration to chlorite-rich assemblages and by locally developed intense hydrolysis producing the quartz-sericite assemblage that is clearly of hydrothermal origin. Diamond-drill-hole logs (Kasteler and Frey, 1949) and published descriptions of mine workings (Emmons, 1903; Kemp, 1904) indicate that the nature of host-rock alteration consists only of a weak propylitic-greenschist type downward within a hundred feet or less from the orebody. The only

TABLE 1. Comparison of Ratios of Pt, Pd, and Minor Platinum-Group Elements in New Rambler Ore and Other Platinum-Group Element Deposits

Platinoid occurrences in placers and in alpine-type and alkalic ultramafic intrusions are not considered. The deposits are classified in three general categories, distinguished as follows:

(I) Platinoid concentrations formed by magmatic processes, associated mainly with sulfide and in some cases chromite segregations in mafic-ultramafic intrusions of diverse character, including komatiitic intrusions (Ungava, Shangani), peridotite-pyroxenite intrusions of tholeiitic affinity (Pechenga, Monchegorsk, Thomson River), large stratified tholeiitic complexes (Bushveld, Great Dyke, Stillwater, Sudbury), and picritic intrusions (Noril'sk, Talnakh). Many deposits of this group overlap class II in character—Cu- and platinum-group element-enriched portions of the deposits have formed at a late stage of the paragenetic sequences under volatile-rich and hydrothermal conditions.

(II) Platinum-group element concentrations formed by hydrothermal processes at intermediate temperatures, with or without an obvious link to igneous activity.

(III) Dunitite pegmatoids of the eastern Bushveld Complex. Cameron and Desborough (1964) consider the Driekop, Mooihoek, and Onverwacht pipes to be of postmagmatic, high-temperature "hydrothermal" replacement origin.

Deposit	Class of deposit	Pd:Pt	Pd:Pt:Σminor PGE	Literature source
A chromitite, Stillwater Complex	I	2.3:1	n.d. ¹	Page et al. (1972)
Merensky Reef (Rustenburg), Bushveld	I	0.3:1	5:19:1	Mertie (1969)
Merensky Reef, avg. E. & W. compartments	I	0.4:1	2:4.6:1	Cousins and Vermaak (1976)
UG2 chromitite, Bushveld Complex	I	0.8:1	1.4:1.7:1	Cousins and Vermaak (1976)
Vlakkfontein pipes, W. Bushveld Complex	I	2.6:1	1.8:0.7:1	Cousins and Vermaak (1976)
Ungava, Quebec	I	0.3:1 to 1.4:1	n.d.	Naldrett and Cabri (1976)
Pechenga, Kola Peninsula, USSR	I	1.7:1	n.d.	Yushko-Zakharova et al. (1967)
Monchegorsk, Kola Peninsula, USSR	I, II	~2:1	n.d.	Yushko-Zakharova et al. (1967)
Hitura, Finland	I, II	1.8:1	n.d.	Häkli et al. (1976)
Noril'sk district, W. Siberia	I, II	3:1 ²	n.d.	Yushko-Zakharova et al. (1967)
Sudbury district, Ontario	I, II	1:1 ³	2:2:1	Stumpfl (1974)
Shangani, Rhodesia	I, II	1.2:1	1:0.8:1	Viljoen et al. (1976)
Thomson River, Victoria, Australia	I, II	1.7:1	n.d.	Keays and Kirkland (1972)
Artonvilla, Messina, Transvaal	II	4.8:1	22:4.5:1	Mihálik et al. (1974)
New Rambler, Wyoming	II	18:1	~1800:100:1	—
Waterburg district, Transvaal	II	0.1:1 to 0.6:1	n.d.	Mertie (1969)
Driekop & Onverwacht pipes, E. Bushveld	III	0.04:1	1:23:1	Cousins and Vermaak (1976)
Mooihoek pipe, E. Bushveld	III	0.2:1	n.d.	est. from Crocker (1969)

¹ Pd:Pt:Rh in the A chromitite is 9.3:4:1 (Page et al., 1972).

² Ginzburg and Rogover (1961) give a figure of 6 as the ratio Pd:Pt in platinum-group element rich sulfide ores at Noril'sk; Pd:Pt reaches 8 to 10 in late hydrothermal chalcopyrite-millerite veins (Yushko-Zakharova et al., 1967).

³ Data given by Mertie (1969) for a paragenetically late Offset deposit are Pd:Pt, 2:1 and Pd:Pt:Rh, 13:6.6:1. n.d. = no data.

sulfide encountered in this alteration facies is pyrite, which occurs as local stringer enrichments. Rather strong hydrothermal alteration extends laterally outward from the orebodies for at least a few hundred feet.

Platinum-group element ratios: Strong evidence that the ore metals have been concentrated by hydrothermal processes is seen in the ratios of platinum-group elements. The ratio of Pd:Pt in New Rambler sulfide ore is near 18:1, and the ratio Pd:Pt:Σ minor platinum-group elements is estimated to be on the order of 1,800:100:1 (analytical data for the concentrations of platinum-group elements and other elements in the ore are presented in a following section). Table 1 provides a comparative compilation of Pd:Pt ratios from available published data for other significant occurrences of platinoid ores. The tabulated data indicate that the New Rambler deposit shows remarkable relative enrichment in palladium—the most soluble of the platinum-group elements. The deposit is singularly poor in Ru, Rh, Os, and Ir, the least soluble platinoids, in contrast to all other deposits for which data could be located.

The ratio of Pd:Pt in mafic rocks in the vicinity of the New Rambler mine averages about 1:1 (Table 2). Palladium is enriched in New Rambler sulfide ore relative to enclosing fresh metagabbroic rocks by a factor of about 7,500, and platinum by about 400. Ginzburg and Rogover (1961, p. 925) have determined partition ratios for base and precious metals between sulfide samples and mafic silicate host rock in the Noril'sk deposit. Enrichment factors in sulfide samples relative to silicate samples at Noril'sk are Pd, 32; Pt, 9. The Noril'sk deposit is believed to be a magmatic sulfide deposit reworked to some extent by late-stage hydrothermal activity (Genkin, 1968, 1959; Stumpfl, 1974). If the partition factors for Noril'sk are presumed to reflect principally magmatic partitioning, as implied by Ginzburg and Rogover, then the enormous difference with Pd and Pt enrichment factors in New Rambler ore suggests that the process which accomplished this partitioning was not magmatic, but some other enrichment process that was far more effective.

Cousins and Vermaak (1976, p. 299) have noted,

TABLE 2. Average Concentrations of Some Trace Metals (in ppm) in Sheared and Unsheared Mafic rocks of the Mullen Creek Mafic Complex in the Vicinity of the New Rambler Mine. (The numbers in parentheses indicate the number of samples analyzed in each group.)

	Pt	Pd	Cu	Ni	Co	Cr	V
Metaleucogabbro (5)	0.020	0.020	61	5.3	2.3	200	149
Metagabbro (13)	0.008	0.002	46	151	59	428	177
Sheared metagabbro (5)	0.008	0.020	63	268	68	1250	213
Metapyroxenite (5)	0.028	0.026	23	468	81	1175	120
Sheared metapyroxenite (3)	0.120	0.113	68	283	58	150	73

with particular reference to evidence from the Sudbury and Noril'sk districts, a general tendency to progressive enrichment of Pd relative to Pt in ore paragenetic sequences. According to these authors, Pd tends preferentially to form solution complexes with volatile elements, e.g., As, Sb, Te, S, that fractionate to a low-temperature milieu. The exceptionally high ratio of Pd:Pt (~18) in New Rambler sulfide ore supports the hypothesis that this deposit has had a relatively low temperature thermal history from beginning to end, compared to other Cu-Ni sulfide ores listed in Table 1, most of which have a wholly magmatic or dual magmatic-hydrothermal history. The Pd-rich postmagmatic hydrothermal copper ores at Messina, Transvaal (Pd:Pt, 4.8), are considered to have been deposited within the temperature interval 270° to 400°C (Mihálik et al., 1974, p. 260).

The low Pd:Pt (1:13 to 1:1.6) in the platiniferous quartz veins of the Waterburg district, Transvaal, might be taken to represent an exception to the trend outlined above. These lodes occur within felsic rocks of the epicrustal series of the Bushveld Complex, and Mertie (1969, p. 44) has suggested that the occurrence of Pt and chromiferous chlorite in these veins points to derivation of at least some of their metal content from mafic rocks of the underlying layered sequence. The mafic rocks of the Bushveld Complex seem to have a relatively low Pd:Pt ratio in general, and Cousins and Vermaak (1976, p. 287) note a trend to relative enrichment of Pt over Pd upward in the complex. Thus, it seems likely that subjacent portions of the layered sequence that contributed metals to the Waterburg lodes may have even lower Pd:Pt, and the general trend to relative Pd enrichment with remobilization of platinum-group elements might hold even in this case.

Other geochemical evidence for hydrothermal origin: Comparison of selected geochemical characteristics of the New Rambler deposit with a number of Au-Cu-bearing quartz-carbonate veins in the district yields significant information. Similarities in structural control and mesothermal character of many of the deposits suggest that the New Rambler

deposit formed during the mineralization episode that affected the rest of the district. The Au-Cu veins are in each case spatially associated with small, hydrothermally altered mafic (dioritic to hornblende) dikes and lenses, but the principal hosts to the veins and the mafic bodies are metamorphosed felsic rocks. Of the known mineralized localities in the central Medicine Bow Mountains, only the New Rambler deposit occurs enclosed in a large volume of cataclastic mafic rocks.³

Comparison of the contents of Ni and Ag, elements typically enriched in mafic rocks, in the two types of deposit shows that New Rambler ores are substantially enriched in both Ni and Ag relative to other ores in the district. Co does not show a significant relative enrichment pattern. Higher concentrations of Ni and Ag in New Rambler ores are taken to reflect important contributions of metals from the mafic host rock to the hydrothermal ore fluids. The locally intensified hydrothermal alteration clearly supports this inference.⁴

To test this hypothesis further, contents of selected trace metals were compared for sheared versus un-sheared mafic rocks from the general area of the mine. These data are shown in Table 2. Sheared metagabbros are significantly enriched in palladium and base metals relative to their un-sheared counterparts. All metals are mobilized in sheared metapyroxenites, and Pt, Pd, and Cu are appreciably upgraded. Sheared metaleucogabbros were not encountered, so no chemical data are available for them; however, the high platinoid and copper contents of un-sheared metaleucogabbros (which, significantly, are somewhat more pyritic) suggests that sheared leucocratic mafic rocks may have been important contributors of Cu and platinum-group elements to the deposit.

A similar hypothesis has been invoked to explain genesis of metamorphic Cu-Ni-Fe sulfide ores in the Allarechensk region, USSR. Zak and Proskuryakov (1971) have proposed formation of this deposit by (1) leaching of Ni, Fe, and Cu from hyperbasites and (2) contemporaneous with tectonic activity, deposition of sulfides of these metals.

³ The presence of high concentrations of platinum-group elements (up to 40 ppm Pd, 30 ppm Pt, and 0.8 ppm Rh) at two small vein occurrences adjacent to the Lake Owens Mafic Complex was noted earlier. Two to three miles west of the Lake Owens intrusion, the larger of these vein-fault systems contains rich Au-Cu ore at several localities (the Albany and Cuprite mines) but no significant quantities of platinum-group elements.

⁴ In a series of hydrothermal experiments on natural rocks, Ellis (1968) was able to leach 0.2 to 4 ppm Cu from andesite in the temperature range 360° to 500°C with solutions in the salinity range 2-4 M NaCl, at 1,500 bars pressure. This concentration of Cu in solution is well within the range known to be capable of depositing economic copper deposits (Wedepohl, 1972, p. 29-F-2).

Evidence for a principally magmatic origin of the deposit

Keays and Kirkland (1972) studied the Thomson River orebody in Victoria, Australia, a deposit with some salient features in common with the New Rambler deposit, viz., a platiniferous Cu-Ni-Fe sulfide paragenesis in hydrothermally altered mafic rock. Keays and Kirkland have convincingly demonstrated that the Thomson River mineralization reflects metamorphism and hydrothermal reworking of a magmatic deposit. Some features of the New Rambler occurrence suggest that consideration should be given to a similar genetic process.

The association of platiniferous chalcopyrite-pentlandite-pyrrhotite ore within a layered mafic igneous complex might be taken ipso facto by some workers as evidence for a predominantly magmatic origin of the metal concentrations. However, the implicitly assumed similarities with well-known deposits of analogous associations are not well substantiated on closer inspection of the deposit. Textures of the ore lend no support to a magmatic origin. If the ore ever had magmatic textures, they have been obliterated by complete recrystallization. The distribution of the ore—disseminated stringers and large irregular pods of massive sulfide, up to tens of feet in thickness and enclosed predominantly in leucocratic facies of the intrusive—has little in common with magmatic deposits at Noril'sk and Sudbury, where immiscibly segregated massive sulfide ore occurs at the floors of the mafic intrusions, or with the thin, widespread ore seam in the pyroxenitic Merensky Reef. No magmatic sulfide segregations have been observed in the extensive outcrop area of mafic complexes in the central Medicine Bows.

Based on the structural, textural, and chemical evidence presented, it is concluded that the New Rambler deposit has formed entirely from hydrothermally introduced constituents and not by in situ reworking of earlier magmatic ores.

Discussion

Although evaluation of variations in mineralization within a deposit as functions of time, space, temperature, pressure, and chemical parameters of the hydrothermal system is a difficult task at best—and major limitations were imposed on this investigation by inaccessibility of the deposit and pervasive supergene alteration—a few meaningful inferences regarding the origin of the deposit can be summarized from the evidence presented.

As mafic rocks throughout the district show evidence of significant redistribution of ore-forming metals during retrograde metamorphism that accompanied major cataclastic activity along the shear zone, it seems likely that the ore metals present in

the New Rambler orebody were mobilized from gabbroic rocks during the peak of diaphoresis and tectonism and were later redeposited during waning stages of the same tectonic-metamorphic event.

Intensified hydration of mafic rocks to greenschist-propylitic assemblages, and the quartz-sericite-pyrite alteration of wall rock (including local appearance of lensatic and stringerlike concentrations of pyrite, represented by sulfide assemblage 1), typify effects developed along walls of flow channels in shear zones throughout the district. The apparent local intensification of these effects in the vicinity of the New Rambler mine is attributable to enhanced permeability at this intersection of shear zones and faults. The principal effect of these hydrolytic alteration processes was base cation leaching, and it appears that these phenomena contributed to significant upgrading of the fluids in concentrations of dissolved metals, notably Cu and platinum-group elements. The somewhat higher contents of Cu, Pd, and Pt in the slightly more pyritic metaleucogabbroic facies of the mafic complex (Table 2) suggest that these rocks may have been particularly favorable contributors of sulfur and ore metals to the metamorphic-hydrothermal solutions.

Localization of the ore at the complex intersection of faults and shear zones suggests that zones of dilatancy in the fluid path may have been influential in focusing activity of the mineralizing solutions. Intensified brecciation characterizes dilatant zones along multiplane faults (Mitcham, 1974, p. 412), and the resulting enhancement of permeability should promote hydrothermal replacement. Constrictions along the flow passage might induce locally intense pressure gradients and throttling. Adiabatic expansion of ore fluids is suspected to be an effective cause of ore deposition (Toulmin and Clark, 1967; Barnes and Czamanske, 1967, p. 374).

Mode of Occurrence of Platinum, Palladium, and Rhodium

Ten platinoid minerals have been encountered in New Rambler ores in this investigation. These are native platinum, sperrylite, and eight tellurides and bismuthotellurides of Pd and Pt. The tendency of Pd and Pt to appear as compounds with Te, Bi, and Sb late in the paragenetic sequence has been noted at Pechenga, Monchegorsk, and Sudbury (Yushko-Zakharova et al., 1967, p. 1110), at Noril'sk and Talnakh (Genkin, 1968, p. 144; Genkin et al., 1973, p. 1008), and in the Merensky Reef (Kingston, 1966, p. 821). Thus, the predomance of bismuthotellurides in the New Rambler paragenesis is consistent with its apparent hydrothermal origin.

A study of the distribution of palladium minerals has shown that chalcopyrite is most commonly the

host in chalcopyrite-secondary pyrite (ex-pyrrhotite) ore. Since the Pd minerals show no sign of instability in the zone of pyritization of pyrrhotite deep in the supergene alteration profile, the relative frequency with which Pd minerals are seen in chalcopyrite and secondary pyrite is believed to represent their distribution in primary chalcopyrite-pyrrhotite ore. Although Pd minerals are more commonly observed enclosed in chalcopyrite than in secondary pyrite by a factor of nearly 3:1, consideration of the fact that the ratio chalcopyrite:pyrrhotite in main-stage ore is about 6:1 indicates that pyrrhotite was actually a preferred associate of Pd minerals. A substantial proportion of the merenskyite and michenerite grains considered as contained in chalcopyrite are intergrown complexly with very small amounts of secondary pyrite and marcasite after pyrrhotite, and the polymineralic aggregate is enclosed in generally massive chalcopyrite. The proportion of Pd minerals enclosed in major sulfide minerals exceeds the proportion enclosed in supergene jasperoid (formerly metagabbroic silicate matrix) by a factor of about 4:1, which underscores the rather strong chalcophile preferences of Pd. As documented in a following discussion, the preferred associations of Pt minerals are essentially the reverse of those of Pd minerals.

Analytical data for 29 bulk ore samples of assemblages 2 and 3 combined were tested for significant element correlations. Chalcopyrite and secondary pyrite are the principal sulfide constituents, but supergene jasperoid is a major gangue constituent of a few samples. The data were tested for correlations using Spearman's nonparametric correlation coefficient, r_s , since concentration-frequency histograms in many cases show non-normal distributions; furthermore, the detection-limit cutoffs for several trace elements (e.g., Rh) and the upper determination limits for major elements (notably Fe) have resulted in censored concentration-frequency distributions. Student's t tests were used to determine levels of significance of correlation coefficients. Results for the lithophile elements V, Cr, and Ti cannot be reported, as these elements were extensively leached from metagabbroic matrix during supergene silicification. These statistical data indicate that Pd associates most significantly with those elements concentrated in secondary pyrite and marcasite—Fe, Ni, and Co. Pd has positive but low correlations with Ag and Cu, metals tied up in chalcopyrite. Positive correlations with all chalcophile elements (and negative correlations with lithophile elements, not tabulated) demonstrate the chalcophile tendencies of Pd.

As Pd minerals are conspicuous in main-stage chalcopyrite-(ex-) pyrrhotite ore and are visible in

about the amounts to be expected from analytical data, it is concluded that Pd occurs in the ore principally as its own minerals and that solid solution of Pd in major sulfide phases is probably slight and relatively insignificant.

However, intensive microscopic examination of five polished slabs of assemblage 1 massive hypogene pyrite containing 60 ppm Pd failed to disclose a single platinoid mineral grain, although Pd minerals are usually visible in Cu-rich main-stage ore carrying as little as 20 to 30 ppm Pd. It is suspected that palladium may occur in significant concentrations in primary pyrite in solid solution. Microprobe analysis of Pd-rich pyrite specimens is in progress in an attempt to determine the presence and significance of Pd solid solution.

Both of two moncheite grains and 6 of the 8 sperrylite grains encountered in 97 polished sulfide ore specimens were enclosed in supergene jasperoid that replaced metagabbroic matrix in disseminated ore. Two other sperrylite grains were intergrown with Pd minerals in a matrix of supergene pyrite (Fig. 5B).

The average Pt content of 15 grains of merenskyite and michenerite analyzed by electron microprobe is 0.4 wt percent Pt (range, n.d. to 2.5 wt percent), from which it can be estimated, on the basis of the ratios of Pd to Pt in merenskyite and michenerite and in the ore (76:4.4 ppm), that 25 to 30 percent of the Pt content of main-stage ore occurs in solid solution in Pd minerals.

The rather low correlation coefficient of Pt with Pd (0.211) indicates that most of the Pt resides elsewhere. Pt shows the strongest correlations with Rh and As (0.449 and 0.437, respectively), consistent with the observed occurrence of these elements as rhodian sperrylite, principally in disseminated ore. Pt also correlates significantly with V ($r_s[\text{Pt-V}] = 0.409$), which occurs in jasperoid in amounts ranging from 50 to 150 ppm in 5 analyzed jasperoid separates, versus 5 to 20 ppm V in separates disseminated sulfides.

These lines of evidence suggest that Pt occurs principally as sperrylite in disseminated ore and to a subordinate extent in solid solution in Pd minerals in sulfide-rich ore.

The rather strong correlation coefficient between Rh and Pt (0.449) is compatible with the observed significant Rh contents of sperrylite, as determined by qualitative microprobe analyses. However, the strength of the Rh-Pt correlation is not as striking as one would expect if this were the only residence of Rh. Some may occur as undiscovered discrete Rh minerals. Low correlations between Rh and chalcophile elements would appear to preclude significant solution of Rh in major sulfide minerals.

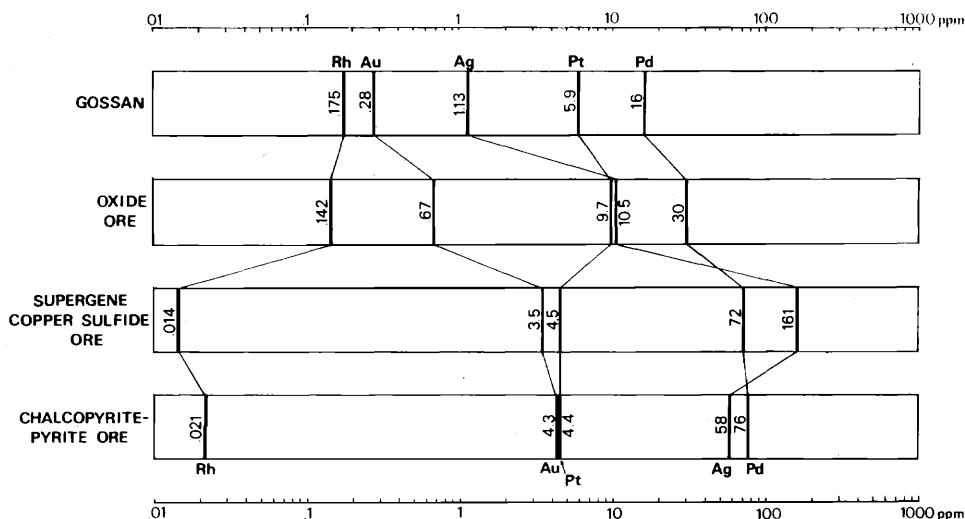


FIG. 6. Schematic section of the New Rambler deposit showing variation of average precious metal contents (in ppm) between horizons of the weathered profile. (Log scale)

Distribution of Precious Metals in Weathered Ore

Figure 6 summarizes analytical data relating to the distribution of precious metals in four levels of the weathered profile of the deposit. The lowermost level corresponds to the zone of supergene pyritization of pyrrhotite and silicification of meta-gabbroic matrix; the data are for 29 samples of assemblage 2 and 3 chalcopyrite-secondary pyrite ore with subordinate amounts of jasperoid matrix. After pyrrhotite replacement is nearly complete, chalcopyrite is electrochemically destabilized and undergoes replacement by covellite, chalcocite, and digenite. The second level from the bottom presents precious metal data for 21 samples composed mainly of Cu sulfides, a little pyrite, and minor amounts of earthy goethitic limonite from the zone of supergene Cu enrichment. This zone is overlain by oxidized copper ore composed mainly of malachite, antlerite, brochantite, cuprite, chrysocolla, and variably siliceous limonite; the uppermost horizon is the surface gossan composed of silicified iron oxide material.

Microscopic examination of the ore indicates that Pd minerals are stable in the zone of supergene pyritization and in the overlying zone of secondary Cu sulfide enrichment, but Pd minerals break down rapidly with the onset of limonitic oxidation of the ore (Fig. 4A); Pd minerals are not visible in the oxidized upper levels of the deposit. The large drops in Pd contents of oxide ore and gossan (Fig. 6) indicate that most of the Pd is being flushed from the system.

The most significant feature of the distribution of

Pt in the weathered profile (Fig. 6) is the abrupt rise in Pt content in the oxide ore horizon. Pt is also higher in gossan material than in sulfide ore. On the basis of only 8 analyses each for the oxide ore and gossan, one might hesitate to speculate on the possible significance of the apparent Pt increase, but corroborative evidence comes from results of solution experiments on the ore.

Since no discrete minerals of the minor platinum-group elements were detected in polished sections, 7 oxide ore samples (1.3 kg total) and 14 primary and secondary sulfide ore samples (1.4 kg total), including assayed samples with the highest Rh, Ir, Ru, and usually high Pt contents, were digested by boiling in $\text{H}_2\text{C}_2\text{O}_4 + \text{HF}$ and then aqua regia, in the hope of obtaining minerals of the minor platinum-group elements in the insoluble residue. Although one unusual metallic crystal obtained by this procedure is yet to be identified, no minor platinum-group element minerals have been recognized. However, 1 native platinum and 53 sperrylite grains were obtained (the identity of each sperrylite grain was established by qualitative microprobe analysis). An interesting feature of the distribution of sperrylite emerged: the mean content of sperrylite grains in 14 samples of sulfide ore was 0.43 grains/100 g sample, with a standard deviation of 0.61; the oxide ore yielded 2.12 grains/100 g sample, standard deviation 1.6. The grain size was equivalent in both groups (30–100 microns).

Thus, there are suggestions that Pt may be undergoing substantial secondary enrichment in the oxidized ore horizon by a solution-redeposition process, possibly by reprecipitation of Pt liberated from solid solution in decomposing Pd-Bi-Te minerals. The

alternative hypothesis that this sperrylite distribution is a relict feature of the primary ore cannot be discounted entirely, and this interesting topic invites more attention.

Like Pt, the Rh leaps dramatically in content in the oxidized levels of the deposit though the Rh-Pt correlation coefficients are low in oxide ore and gossan (0.238 and 0.178, respectively). The residence of Rh in the oxidized horizons is not known, but preliminary evidence suggests it is not in sperrylite.

Iridium and ruthenium were rarely detected in the ore (detection limit 0.5 ppm for each). It is no doubt significant that Ir was detected in only 1 of 45 sulfide samples and Ru not detected in any, whereas Ir or Ru was detected in 3 of 8 gossan samples. Travis et al. (1976) report that retention of Ir in gossans of nickel sulfide deposits in Western Australia is exploited in geochemical prospecting for these nickel ores.

Considering the low Au values in the ore, the frequency with which electrum has been seen suggests that Au occurs in the ore mainly in the metallic state. Yellower color and greater resistance to dissolution in acid-digestion experiments indicates that gold grains in oxide ore have undergone preferential leaching of alloyed Ag. Data of Figure 6 suggest that some Au is also undergoing solution in the oxidized levels of the deposit, but the evidence does not reflect secondary enrichment of Au in underlying horizons.

Silver, on the other hand, exhibits strong leaching from the oxidized upper levels of the deposit and dramatic secondary enrichment in the zone of supergene Cu sulfide enrichment. The Ag in enriched ore occurs in covellite (mean 119 ppm Ag, 6 mineral separates), chalcocite (mean 162 ppm Ag, 4 separates), cuprite (mean 250 ppm Ag, 2 separates), and in "deep-zone" nonsiliceous, earthy limonite (mean 212 ppm Ag, 5 separates). The only secondary Ag mineral recognized in the ore is native silver in partially oxidized assemblage 3 ore specimens, where it occurs in calcite-filled solution cavities (Fig. 5A) and as small leaves and grains in the interstices of well-crystallized hematite and goethitic limonite. Although the Ag content of deep-zone earthy limonite separates (limonite associated with abundant sulfides in enriched assemblage 2 ore) is high—212 ppm—no Ag minerals were recognized in polished section.

Conclusions

(1) The New Rambler deposit is believed to have formed entirely by hydrothermal processes. Its high concentration of platinum-group elements is testimony to the effectiveness of hydrothermal systems in transporting and concentrating these metals, a fact of

general significance that is receiving belated recognition.

(2) In various stages of the deposit's evolution, partitioning of platinoid metals according to their disparate solubilities has been apparent. The relative proportions of platinum-group elements in the ore compared to those in metagabbroic host indicate strong solubility fractionation during leaching of host rocks; relative to mafic host rocks, Pd has been upgraded in sulfide ore by a factor of about 7,500, Pt by 400, and other platinoids by probably less than 100. Contrast in geochemical character is well displayed in the weathering regime by the variation of Pd:Pt from approximately 17 to 16 to 3.1 to 2.7 in the chalcopyrite-secondary pyrite ore, supergene Cu sulfide ore, oxide ore, and gossan horizons, respectively. The distribution of metal values in the weathered profile reflects appreciable leaching of Pd in the strongly oxidized levels. A more than twofold enrichment of Pt in oxide relative to sulfide ore and nearly tenfold enrichment of Rh in oxide relative to sulfide ore may reflect supergene solution activity. Ir and Ru values rise significantly at the weathered outcrop.

(3) Platinum and palladium are believed to occur in sulfide ore principally as discrete platinoid minerals. A significant proportion of the Pt occurs in solid solution in Pd minerals, mainly merenskyite and michenerite. Rh, Ru, Ir, and Os are probably tied up mostly as trace substituents in Pt and Pd minerals.

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