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REVIEW OF PLATINUM-GROUP METAL GEOCHEMISTRY AND THE MAJOR OCCURRENCES IN THE WORLD

By

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INTRODUCTION

Surveys of the geochemistry of the platinum-group elements (Wright and Fleischer, 1965; Yushko-Zakharova and others, 1967; Mertie, 1969; Crocket, 1969, 1979; McBryde, 1972) illustrate the problems that insufficient analytical data on geological materials create in presenting a unified geochemical discussion. Although early low-level determinations of the platinum-group elements appear to contain errors, and the more modern data have been limited predominantly to analyses of mafic and ultramafic rocks and their associated Ni-Cu-platinum-group metal ore deposits, the major features and characteristics of platinum-group metals are known. In this paper we will outline the major platinum-group-metal producing areas of the world, indicate some potential areas in the United States, identify geologic environments that are favorable for finding concentrations of platinum-group metals, discuss sampling techniques for geologic materials, and make a guess at the geochemical cycle and relative concentrations in geologic materials. As a result we can identify some major problem areas in platinum-group-metal geochemistry.

GEOLOGIC OCCURRENCES OF THE PLATINUM-GROUP METALS

The major minable deposits of the platinum-group metals occur with nickel-copper and copper lodes associated with mafic and ultramafic rocks and as residual concentrations in placer deposits. General references to the geology and geochemistry of the platinum-group elements include Mertie (1969), Quiring (1962), Wright and Fleischer (1965), Crocket (1969), and Economic Geology (1976). With the exceptions of the potentially economic occurrences in the Stillwater Complex, Mont.; Duluth Gabbro Complex, Minn.; and Crillion-La Perouse Complex, Alaska, virtually all the known platinum-group minerals produced in the United States came or come from placers and (or) as byproducts of copper refining. Mafic and ultramafic rocks form at least three distinctive types of igneous complexes (Jackson and Thayer, 1972) with various subtypes (Naldrett and Cabri, 1976) which form the basis for the classification of platinum-group-bearing lode deposits.

CLASSIFICATION OF DEPOSIT TYPES

Platinum-group metal deposits can be classified or grouped as follows based on Page and others (1973), Naldrett and Cabri (1976), and the IGCP Project 161 (1979): (1) Lodes associated either with stratiform-floored, tabular ultramafic and mafic complexes or with sills and sheets equivalent to flood basalts; the lodes occur in the layered sequences as thin, laterally continuous horizons, as gravity accumulations of sulfides at the margins or as contact-metamorphic deposits near the margins of the complexes; (2) Lodes associated with concentric, roughly cylindrical, zoned complexes of ultramafic and mafic rocks; the lodes occur in the layered portions or in the margins of the masses; (3) Lodes in alpine complexes of ultramafic and mafic rocks; the lodes occur in discontinuous lenses; (4) Lodes in other mafic rock environments which include a variety of irregularly shaped or dike-shaped intrusive and extrusive rocks; the lodes occur as base- and precious-metal deposits in contact zones, in gravity-differentiated sulfide concentrations, and in vein systems; (5) Residual concentrations of precious metals in placer deposits consisting of unconsolidated alluvial deposits in present or ancient stream valleys, terraces, beaches, deltas, and glaciofluvial outwash, and in lithified placers of similar origin; and (6) Minor occurrences of platinum-group metal concentration which include those associated with alkalic intrusive rocks (syenites) with copper mineralization, carbonatites, gold-quartz-copper veins, hydrothermal vein systems including base and precious metals but that also contain complex telluride and bismutho-telluride mineralization and in porphyry copper deposits as byproducts.

MAJOR KNOWN PRODUCING AREAS OF THE WORLD

Canada, Colombia, South Africa, and Russia have been the major producers of platinum-group metals from both lode and placer deposits. Other areas have at times supplied some of the world's platinum-group metals; minor amounts have and do originate at times from deposits including ones in Australia, Burma, Brazil, Chile, Ethiopia, Finland, Japan, New Zealand, Papua, Rhodesia, Sierra Leone, United States, Zaire, and Zambia. Estimates of platinum-group metal resources by the U.S. Bureau of Mines indicate that South Africa has over 2,000 million ounces; U.S.S.R., 400 million ounces; North America, 316 million ounces; Rhodesia, 100 million ounces; and Columbia, 5 million ounces.

Platinum Deposits in South Africa

The Bushveld Igneous Complex, a stratiform intrusion, covers an area of 260,000 mi^2 in the Central Transvaal and contains the world's largest resources of platinum-group metals in one intrusive geologic mass. Vermaak and Hendriks (1976), Vermaak (1976), Brynard and others (1976), Gruenewaldt (1976, 1977), Merwe (1976), and Schwellnus and others (1976) have recently reviewed the details of the geology, mineralogy, and geochemistry of these occurrences. The Merensky Reef, the UG-2 chrome seam, and Platreef in the Critical zone of the Bushveld contain the major resources of platinum-group metals, estimated on the order of 20 to 22 billion troy ounces of platinum-group metals plus gold (Gruenewaldt, 1977). The Merensky Reef is a cumulate orthopyroxene-chromite pegmatoid, locally with cumulate olivine, and with interstitial plagioclase and clinopyroxene. It varies in thickness from a few feet to 50 ft, has been traced along strike for about 225 miles, and has an average grade between 0.25 and 0.35 troy ounces/ton platinum-group metals. Copper and nickel sulfides are present and a representative mill grade would assay 0.19 percent Ni, 0.11 percent Cu (Newman, 1973). Gruenewaldt (1977) estimates that there are 0.176 troy ounces/ton of recoverable platinum group in the Merensky Reef. The UG-2 chrome seam has a similar extent by higher grade, estimated at 0.192 troy ounces/ton of recoverable precious metals (Gruenewaldt, 1977) and low amounts of copper or nickel. The Platreef is estimated to have a recovery grade of precious metals of 0.096 troy ounces/ton (Gruenewaldt, 1977) and no copper or nickel. The major mines in the Merensky Reef include Bafokeng South, Bafokeng North, and Widebeestfontein operated by Impala Platinum Ltd., and nine shafts and inclines in the Rustenburg section, three in the Union Section, one in the Amandebult section, and two in the Atok section operated by Rustenburg Platinum Holdings, Ltd. Rustenberg is also experimenting with a pilot plant to recover platinum-group metals in material from the UG-2 chrome seam in the Driekop area.

Gold mines in the Witwatersrand conglomerates produce about 5,000 oz per year made up of 12 percent Pt, 35 percent Ir, 38 percent Os, 14 percent Ru, 1 percent Rh, and trace Pd (Newman, 1973). The geology and mineralogy of these deposits have been recently summarized by Cousins and Kinloch (1976) and Feather (1976).

Other platinum concentrations have been reported from the base of the Insizwa Intrusion, a differentiated sill in the Karoo beds, the Messina copper mine, Palabora copper mine which recovered about 2,765 troy ounces of Pt and Pd per year (Cousins, 1976), Prieska and O'okiep copper deposits, dunite pipes in the Lydenburg district, and the Waterberg brecciated quartz lodes where high values occur in irregular patches.

Major Platinum Deposits in Russia

Noril'sk, Petsamo, and the Urals are the three major platinum-producing areas in Russia although there are over 450 reported occurrences in the literature. Till and Page (1979) have collected and summarized published information on these occurrences in the U.S.S.R. Krauss and Schmidt (1979) estimate that Russian reserves are 6,221 metric tons. At Noril'sk, located in the north-central part of the Soviet Union in the Krasnoyarsk territory, the deposits occur as either high-grade massive bodies and veins or disseminated bodies found at the intrusive contacts of diabase and gabbro with limestones, shales, and sandstones. According to Newman (1973) the massive ore carries up to 2.16 percent Cu, 1.23 percent Ni 0.1 percent Co, and 0.305 troy ounces/ton platinum-group metals, whereas the disseminated deposits average 0.1-0.3 percent Cu, 0.1-0.3 percent Ni, and 10.6 troy ounces/ton platinum-group metals. About 85 percent of the platinum-group metals produced in U.S.S.R. originate from the Norkl'sk deposits (Krauss and Schmidt, 1979). The Petsamo deposits in the Pechenga-Monchegorsk region of the Kola peninsula are associated with picritic rocks. The massive sulfides average 3.5 to 4 percent Ni, 1.8 percent Ni, and contain 0.042 troy ounces/ton Pd (Naldrett and Cabri, 1976). According to Newman (1973) the Ural placers were being worked by dredges with grades between 0.01 and 0.9 troy ounces/ton but only with small production. These deposits in stream gravels concentrated from concentric ultramafic and mafic complexes were very rich in platinum and have been worked since 1824.

Platinum Deposits in Canada

Platinum-group metals in Canada are produced mainly as a byproduct of nickel-copper production. Most of the nickel ores come from the Sudbury Complex, a large stratiform, oval-shaped intrusion with dimensions along the axes of 37 by 17 miles in Ontario. The concentration of platinum-group metals averages about 0.026 to 0.029 troy ounces/ton (Allen, 1960) with about 40 percent Pt, 40 percent Pd, and 20 percent Os, Ir, Ru, and Rh (Newman, 1973). Canada also produces nickel-copper ores with byproduct platinum-group metals from the entire spectrum of ultramafic and mafic complexes which occur in Manitoba, Ontario, Quebec, and British Columbia.

Platinum Deposits in Columbia

The major placer deposits in Columbia occur in the Nechi-Porce and Atrato and San Juan river drainages in departments of Antioquia and Choco, respectively (Wokittel, 1961). Pato Consolidated Dredging Company operated the placer dredges on the Nechi-Porce drainage. The Choco Pacifico Mining Company did the placering in the Atrato and San Juan Rivers. Both areas produce predominantly gold; Pata Consolidated Dredging Company used to produce about 100,000 ounces of gold per year with an Au-Pt ratio of greater than 10,000:1. Gold production in the Choco drainage was about 30,000 ounces in 1965 and has apparently been declining and the Au-Pt ratio is probably of the same order of magnitude. Both Pato and Choco Companies were bought out in 1974. All dredging now is done by Companie Mineros Colombianos, South America.

Platinum Occurrences in Other Parts of the World

Producing platinum deposits in other parts of the world include those in Australia, Rhodesia, and Finland from byproducts of copper-nickel mining. In Australia and Rhodesia some platinum-group metals are produced as a byproduct of copper-nickel mining of massive sulfides associated with komatiitic rocks. In Finland, the Hitura nickel-copper deposit contains 0.006 troy ounces/ton Pt and 0.005 troy ounces/ton Pd and produces about 300,000 tons or ore per year (Hakli and others, 1976).

MAJOR KNOWN POTENTIAL PLATINUM-GROUP METAL AREAS IN THE UNITED STATES

After the boom of placer mining and prospecting and prospecting for precious metals in the United States in the late 1800s and early 1900s, exploration for platinum-group metals essentially ceased because of the availability of foreign supplies and also the lack, until the mid-1960s, of directly applicable modern geological, geothermal, and geophysical techniques for finding new potential deposits. Blair and others (1977) and Page and Tooker (1979) have summarized in map form the platinum-group metal occurrences in lodes and placers in the United States. With the development of analytical techniques for the platinum-group elements in geologic materials at the low parts-per-billion level (Haffty and Riley, 1968) and a better understanding of the geochemistry and geology of the elements, modern programs of exploration began to find new occurrences. Nevertheless, large areas of Alaska remain unexplored for these elements, and some environments in the conterminous United States remain unexamined in detail. In addition to the earlier known Goodnews Bay placer deposits, three other major potential platinum-group-producing areas were identified in the mid-1960s and 1970s: the Stillwater, Duluth, and Crillion-La Perouse complexes.

The Stillwater Complex, Southwestern Montana

The Stillwater Complex, a large tabular, stratiform mass of internally conformable, layered mafic and ultramafic rocks of Precambrian age, is located in Stillwater, Sweetgrass, and Park Counties, south of Columbia and Big Timber, Mont. The complex has been divided into several major stratiform zones by Jones and others (1960), Hess (1960), Jackson (1961, 1963), Page and Nokleberg (1974), and Segerstorm and Carlson (1977). Each zone contains platinum-group metals in various concentrations (Page and Jackson, 1967; Page, 1971; Page and others, 1969, 1972; Page and others, 1976; and Johns-Manville Press releases February 1975 and May 31, 1978), but at the present time only one zone has economic interest specifically for platinum-group elements. All of the units within the complex--the Basal zone, Ultramafic zone, Banded zone, and Upper zone--originated from differentiation of basaltic magma under changing physical and chemical conditions which produced the repetitious layered sequence of rocks and the concentration of the platinum-group elements.

The major occurrences of platinum-group elements in the complex are in three zones: (1) the Basal zone, where they are associated at low concentration levels with massive and disseminated copper-nickel sulfide concentrations; the platinum-group elements potentially could be produced as as byproduct from any future mining operations in this zone; (2) the Ultramafic zone, specifically in the chromitite horizons, where platinum, palladium, rhodium, iridium, and ruthenium concentrations range from the limits of determination up to 0.26 troy ounces/ton Pt, 0.35 troy ounces/ton Pd, 0.05 troy ounces/ton Rh, 0.017 troy ounces/ton Ir, and 0.029 troy ounces/ton Ru; the higher concentrations are found in the lowest, thin chromitite; the chromitite horizons that were mined for chromite contain an average of between 0.005 and 0.007 troy ounces/ton platinum+palladium+rhodium; (3) the Banded zone as a thin (0-20 ft, averaging 5-7 ft) tabular (24-28 miles long) zone dipping northward, exposed over 2,000-3,500 ft of topographic relief and containing platinum-group metals, copper, nickel in olivine$\pm$orthopyroxene$\pm$plagioclase cumulates. There are other known minor occurrences of platinum-group elements at other positions in the complex (Howland and others, 1936; Page and others, 1976).

The platinum-group metals zone in the Banded zone is being and has been explored by the Johns-Manville Company by geologic mapping, geochemical sampling, surface trenching, diamond drilling, and an adit from which a 100-ton sample was collected for metallurgical testing. According to Johns-Manville's press releases, one section has been identified that is 18,000 ft long, averaging 7 ft thick, with an average grade of 0.65 troy ounces/ton and with a Pd-to-Pt ratio of 3.5 to 1, and another section that has an average grade of 0.43 troy ounces/ton over 5 ft of thickness with a similar Pd-to-Pt ratio.

The Duluth Complex, Minnesota

The Duluth Complex, a large mass of mafic and ultramafic rocks, extends from Duluth on Lake Superior in an arc shape to the northeastern part of Minnesota to the Canadian border through parts of the Boundary Waters Canoe area. Geologic studies in the Duluth Complex have subdivided it into four major rock groups (Bonnichsen and Tyson, 1975): The Troctolitic series, Anorthositic series, Gabbro, and Granophyre. The complex consists of several separate intrusions and the area of particular interest between Hoyt Lakes and the South Kawishiwi River, southeast of Ely, Minn., has been called the South Kawishiwi Intrusion. It consists of three major units: (1) a Basal zone, varying from 200 to 1,200 ft in thickness, but generally 400 to 800 ft, and consisting of a heterogeneous assortment of troctolite, gabbro, norite, picrite, and dunite, (2) an augite troctilite unit, and (3) an overlying troctolite unit with slightly different characteristics. In this area 2.2 billion tons of copper-nickel mineralized rock at a cutoff grade of 0.5 percent combined nickel and copper were estimated to be present by Sims and Morey (1974). A more recent estimate based on 324 drill holes in an overlapping area of 42.2 mi^2 (Minnesota Dept. Nat. Resources, 1977) gives resources of 2.6 billion tons of ore with an average grade of 0.66 percent Cu and 0.20 percent Ni, or 4.4 billion tons with a cut off grade of $\geq$0.5 percent Cu. A 120-ton bulk sample, part of a 10,000-ton sample removed by International Nickel Company, was examined and tested metallurgically by the U.S. Bureau of Mines (Schluter and Landstrom, 1974). They produced a flotation concentrate that contained between 0.021 and 0.036 troy ounces/ton Pt, 0.120 and 0.128 troy ounces/ton Pd, 0.002 to 0.003 troy ounces/ton Rh, 0.001 and 0.002 troy ounces/ton Ir, and 0.001 to 0.004 troy ounces/ton Ru. From the values given for the INCO Spruce Pit, viz: 0.00107 ounces/ton Pt and 0.00304 ounces/ton Pd (Minnesota Dept. Nat. Resources, 1977) extrapolated to the rest of the area, the platinum resources in 4.4 billion tons of ore are estimated to be about 18 million ounces. The distribution of platinum-group elements in this part and the other portions of the Duluth Complex is not adequately known, so that a more comprehensive evaluation cannot be made at this time.

Crillion-La Perouse Complex, Alaska

The Crillion-La Perouse Complex, in the southern Fairweather Range, Alaska, contains the Brady Glacier deposit located near the base of the 10,000-m-thick, synformal-shaped layered stratiform intrusion. The deposit consists of disseminated copper-nickel sulfides and local massive sulfides in gabbro and peridotite (Czamanske and others, 1977). Sulfide minerals are pyrrhotite, pentlandite, chalcopyrite, and violarite; platinum-group minerals have not been identified.

There are greater than 100 million tons of 0.5 percent Ni and 0.3 percent Cu ore, probably 95 percent of which is disseminated ore. The average platinum-plus-palladium content of the disseminated ore is 0.005 troy ounces/ton and of the massive 0.042 troy ounces/ton with a ratio of Pt to Pd of 0.8. The limits of the ore body have not been determined since it extends under moving glacial ice.

Goodnews Bay, Alaska

In the valley of the Salmon River, Alaska, platinum-metal-bearing placers occur in two paystreaks that have been exploited by the Goodnews Bay Mining Company (Mertie, 1969). Production from 1927 to 1969 is estimated to have been considerably more than half a million troy ounces with weighted mean percentages of the metals mined from 1936 to 1970 of 82.31 percent Pt, 11.28 percent Ir, 2.5 percent Os, 0.17 percent Ru, 1.29 percent Rh, 0.38 percent Pd, and 2.24 percent Au. The major alloys present are ferroplatinum and osmiridium with minute amounts of cooperite, laurite, sperrylite, and mertieite also occurring (Page and others, 1973). Although mining operations have shut down, it is reported that there are an estimated 40 million cubic yards of gravels in the Salmon Creek and Western Creek placers yet to be exploited.

GEOCHEMICAL CYCLE OF PLATINUM-GROUP METALS

For most elements a discussion of the geochemical cycle of an element traces the distribution and residence of the element in cosmic abundance, the core, mantle and crust of the Earth, volcanic and intrusive igneous rocks, through the weathering and erosion cycle into sedimentary rocks, in hydrothermal processes and in metamorphic rocks. For the platinum-group elements, relatively meager information exists for samples from these geologic environments and estimates made for their distribution and residence should claim a low level of accuracy, especially for crustal abundances, volcanic rocks, siliceous and intermediate igneous rocks, hydrothermal and weathering processes, sedimentary rocks, and metamorphic rocks. Most modern analytical data are available for meteorites, ultramafic and mafic rocks, and some Ni-Cu sulfide ore deposits.

The major characteristics of the platinum-group elements are that they are siderophile (concentrated in metallic phases) and chalcophile (concentrated in sulfide phases); they are clearly more abundant in ultramafic rocks than in silicic rocks, and there is some evidence that Pt and Pd moves in the weathering cycle (Fuchs and Rose, 1974). The platinum-group metals occur naturally as alloys, sulfides, arsenides, tellurides, antimonides, bismuthides, or combinations thereof. Over 75 species of named minerals have been well characterized and in 1975 there were about 65 incompletely characterized and unnamed species (Cabri, 1976). For instance, the major minerals in the Merensky Reef are braggite, cooperite, laurite, sperrylite, and Pt-Fe alloy, although many of the more complex compounds are present (Vermaak and Hendriks, 1976). In many occurrences the platinum-group mineralogy is just beginning to be worked out and the phase relations between the different minerals are essentially unknown.

For comparing diverse types of platinum-group metal occurrences, where the concentration levels range from less than a part per billion (ppb) to hundreds of parts per million (ppm), a feasible technique is to ratio the data from each element to chrondrite abundance and talk about enrichment of depletion with respect to chrondrite abundances. Chrondrite abundance estimates of McBryde (1972) are Pt, 1.5 ppm; Pd, 1-2 ppm; Rh, 0.2 ppm; Ru, 1.0 ppm; Os, 0.7 ppm; and Ir, 0.5 ppm and are used in the following discussion to compare with other rocks by ratioing with the determined values. This also appears to give characteristic patterns that appear to characterize the geologic environment. For example ultramafic rocks and their ores formed from the differentiation of basaltic magmas have the reverse patterns of ultramafic rocks associated with ophiolites or rocks suspected to originate as oceanic mantle and crust.

Fragmental data are beginning to appear for sedimentary environments especially for deep-sea sediments like calcareous and siliceous oozes and pelagic clay (Crocket and Kuo, 1979). The average Pd content is 3.5 ± 2.8 ppb and Ir content is 0.31+0.14 ppb. Platinum-group metals have been found in manganese nodules and analyses suggest that this environment should be pursued as a byproduct source of platinum-group elements.

GEOCHEMICAL SAMPLING OR PROSPECTING

Prospecting for platinum metals has been, and continues to be, rather intuitive. Perhaps the most successful approach has been to look for placer accumulations of platinum-group metals by standard panning techniques and attempt to find the lode source. After location of the lode source, normally a mafic or ultramafic body, prospecting concentrated on locating the oxide and (or) sulfide-rich zones with which the platinum-group metals are commonly associated. Geochemical prospecting involves collecting a variety of sample media or concentrating on only one. Various sample media include rocks, soils, stream sediments, and vegetation. All of these have been used for attempting to find lode sources of the platinum-group metals.

One of the more successful exploration programs aimed at the discovery of platinum-group metal occurrences has been described by Conn (1979). Johns-Manville Corporation focused on the Stillwater Complex and employed a variety of methods including traditional prospecting geologic mapping, soil and silt geochemistry, magnetometer, induced polarization, very low frequency electromagnetic surveys, trenching diamond drilling, and underground exploration. However, their success was due to application of geochemistry to soil and silt samples and having a ready source of low level Pt and Pd analyses. Some of the details of the soil geochemistry are discussed by Fuchs and Rose (1974).

AREAS FOR FURTHER RESEARCH

Within the limited knowledge of the geochemistry of the platinum-group elements and rapidly expanding accumulation of new mineralogic and analytical data, the areas for further research on the geology and geochemistry of the platinum-group metals are broad and varied. Basically, there is a need for the development of rapid, precise techniques for determing low levels of Os, less than 10 ppb, in the diversity of geologic materials that would be necessary to understand the geochemical cycle of osmium. At present we know the least about Os and Ru in geologic materials. Essential to any increase in understanding of the platinum-group metals distribution and geochemical behavior is the collection of analytical data from as many different geologic materials as possible. This includes common sedimentary rocks, metamorphic rocks, siliceous igneous rocks, and normal rock-forming minerals. The collection of this type of data will push the lower limits of the presently available analytical methods. One of the more intriguing fields for experimental and field-oriented research is in the low temperature, weathering, and transportation cycle of the platinum-group metals.

Information from such research would be directly applicable to exploration for platinum-group metal deposits. One of the geologic environments that seems to have been neglected in exploration, in the United States and the other parts of the world in a search for new platinum-group metal deposits, is that in which the Noril′sk deposits occur. The geologic combination of evaporite sequences, diabase intrusions, and rifting-type tectonics probably should be reassessed.

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