Southwick

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WORKSHOP ON THE APPLICABILITY OF GOLD AND PLATINUM-GROUP-ELEMENT MODELS IN MINNESOTA

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WORKSHOP ON THE APPLICABILITY OF GOLD AND PLATINUM-GROUP-ELEMENT MODELS IN MINNESOTA

Edited by G.B. Morey

Convened with the support of the Minnesota Legislature through the Mineral Diversification Program,
as administered by the Minnesota Minerals Coordinating Committee

PREFACE

The geology of Minnesota is highly varied and contains combinations of lithologic and structural factors that are known to be associated with important deposits of metallic minerals elsewhere in the world. Despite this broadly favorable potential for a diverse array of deposit types, however, only the world-class deposits of iron ore have yet been discovered. This suggests that we know too little about the geology, too little about the criteria for recognizing nonferrous mineral deposits, or, as is probably the case, too little about both. As a step toward remedying these deficiencies, a mineral deposit workshop was convened in April 1989 with support from the Minnesota Legislature through the Mineral Diversification Program, as administered by the Minnesota Minerals Coordinating Committee (W.C. Brice, Minnesota Department of Natural Resources, Division of Minerals; P.C. Grew, Minnesota Geological Survey; K.J. Reid, Mineral Resources Research Center; T.B. Johnson, Natural Resources Research Institute). The topic of the workshop was a discussion of mineral deposit models applicable to gold and the platinum group of elements (PGE) in Minnesota.

Co-convenors of the workshop were Priscilla C. Grew (Minnesota Geological Survey), Michael P. Foose (U.S. Geological Survey), and Steven A. Hauck (Natural Resources Research Institute, University of Minnesota, Duluth). Professor Samuel S. Adams (Colorado School of Mines) provided special assistance in planning the workshop program. Industry participation was coordinated by Keith Laskowski (Newmont Exploration, Ltd.) and William C. Ulland (American Shield), both of the Minnesota Exploration Association.

The body of this report consists of two parts—an overview of Minnesota's geologic framework, by D.L. Southwick, and a summary of the workshop discussions. Minnesota Geological Survey staff members who contributed to the summary were Jane Cleland, Priscilla Grew, Mark Jirsa, Peter McSwiggen, James Miller, G.B. Morey, and David Southwick. Samuel S. Adams critically reviewed the summary, as did Frederick J. Sawkins (University of Minnesota), who also added substantially to the discussion of the Hemlo and Homestake gold deposits. Sawkins also provided preprints of selected parts of his textbook, "Metal deposits in relation to plate tectonics," 2nd edition, 1989, to be published by Springer-Verlag.

CONTENTS

ILLUSTRATIONS

APPENDICES

AN INTRODUCTION TO MINNESOTA'S GEOLOGIC FRAMEWORK AND ITS IMPLICATIONS FOR MINERAL EXPLORATION

D.L. Southwick

Our understanding of Minnesota's Precambrian framework has improved significantly within the past decade through the combined application of high-precision aeromagnetic and gravity surveys, follow-up scientific test-drilling, and outcrop-based geologic mapping. The revised interpretive maps of Precambrian terranes in the drift-covered parts of Minnesota are better constrained, more detailed, and more sophisticated than previous interpretations, and therefore provide new regional targets and target concepts for the exploration industry to investigate. Equally important is the new information being developed on the distribution, thickness, and stratigraphic complexity of the Cretaceous and Quaternary overburden in Minnesota, because this information provides realistic parameters on the technical difficulties and costs to be faced by explorationists working here.

The major Precambrian subdivisions of Minnesota are (1) the Superior Province (Superior Craton) of Archean age, which includes the dominantly late Archean greenstone-granite terrane in the north and the middle to late Archean gneiss terrane in the south; (2) the Penokean orogen of Early Proterozoic age; (3) the Sioux Quartzite of poorly documented Early or Middle Proterozoic age; and (4) the Midcontinent rift system, a continental rift that developed late in the Middle Proterozoic (ca. 1100 Ma). A current interpretation of this lithotectonic framework for the Precambrian basement of the state is shown in Figure 1.

To date, belts of Archean metavolcanic rocks within the Superior Craton in northern Minnesota (the so-called greenstone belts) and the major fault zones within them have attracted the largest gold exploration interest because of their geologic similarity to producing greenstone-belt gold districts in Canada. The Vermilion district is a moderately well exposed greenstone belt within the Wawa-Shebandowan subprovince of the Superior Craton that has seen several cycles of gold and base-metals exploration. Farther west, in the same subprovince, a less well exposed greenstone belt in northern Itasca County has also attracted exploration interest. The northern Itasca area is currently being remapped by the Minnesota Geological Survey under a combination of geophysical, drilling, and mapping initiatives, and much geological detail is emerging. About 70 km (45 mi) northwest of the Itasca area, at the southern margin of the Wabigoon subprovince, a strongly deformed greenstone belt that crosses northern Koochiching and Lake of the Woods Counties has been explored several times for both base metals and gold. This belt lies within the International Falls and Roseau 1° x 2° quadrangles being investigated under the Conterminous United States Mineral Appraisal Program (CUSMAP) of the U.S. Geological Survey. Other geophysically identified greenstone belts in the westward extensions of the Wawa-Shebandowan and Wabigoon subprovinces lie beneath prohibitively thick overburden (Fig. 2) and have attracted little exploration interest.

An intriguing and little-understood subunit of the greenstone-granite terrane is the so-called "quiet zone" (Fig. 1). Geophysical expressions over this area are relatively flat and featureless, comparable to those found over metasedimentary belts elsewhere in the Superior Craton, and yet the drill reveals a varied geology that includes volcanic and plutonic as well as sedimentary

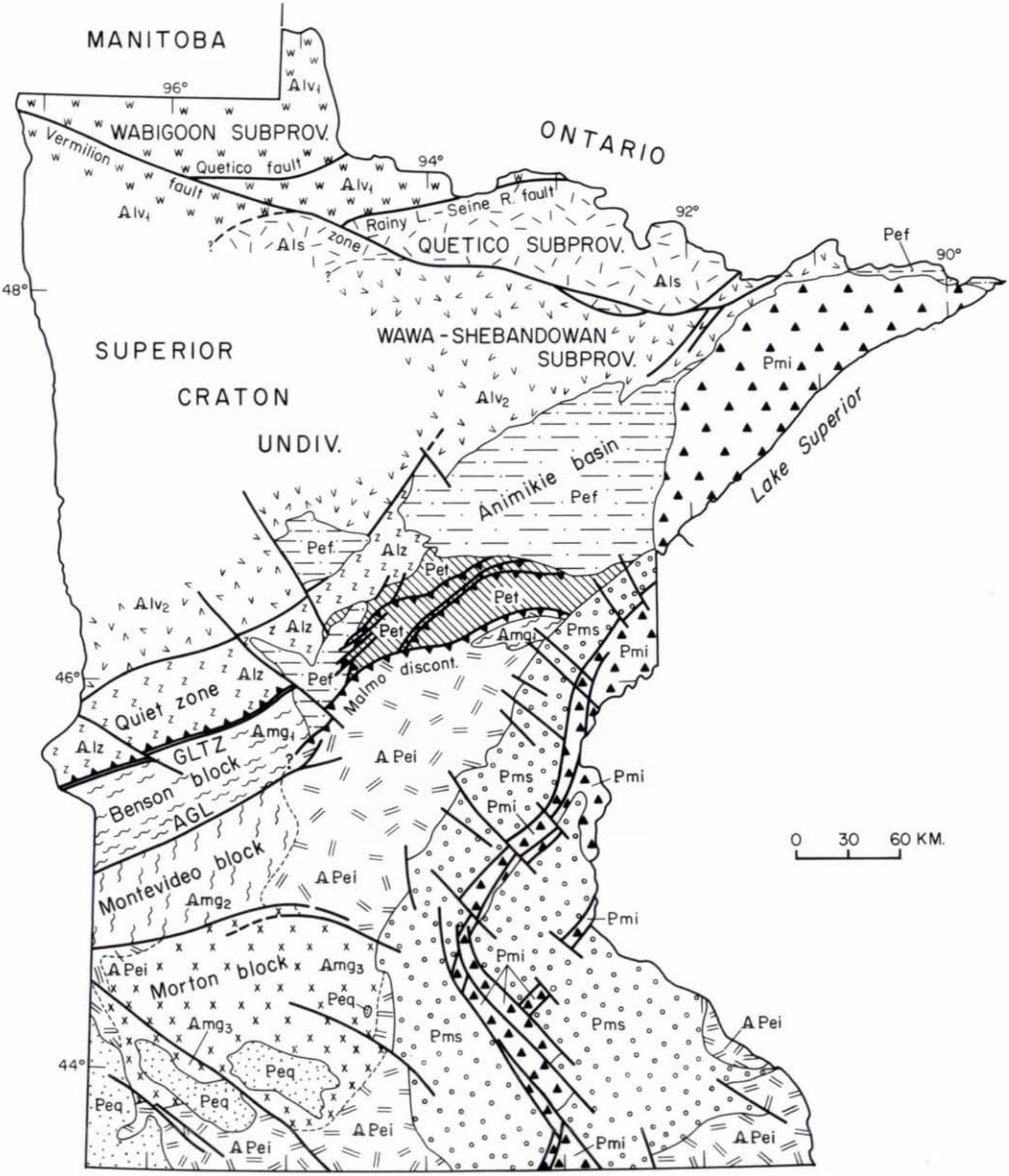

Figure 1. Simplified tectonic map of Minnesota compiled from published sources and unpublished work in progress at the Minnesota Geological Survey. Age data tabulated in explanation are from published sources except as noted. Ages from named Archean subprovinces are from Canadian sample suites.

EXPLANATION

MAJOR PRECAMBRIAN TERRANES OF MINNESOTA

TECTONIC ELEMENT		PRINCIPAL ROCK TYPES	AGE
Midcontinent rift system			
late- and post-rift	Pms	Fluvial and lacustrine clastic sedimentary rocks	Middle Proterozoic; 1100-~1050 Ma
syn-rift	Pmi	Basalt, rhyolite, gabbroic intrusions; minor interflow sedimentary deposits	
Sioux Quartzite basins	Peq	Fluvial, sand-dominated redbed sequences in basins that may be fault-controlled	Early Proterozoic; probably between 1760 and 1630 Ma
Penokean orogen			
foredeeps	Pef	Turbiditic graywacke-shale sequences	
fold-and-thrust belt	Pet	Passive-margin metavolcanic and meta-sedimentary rocks, tectonically imbricated	Early Proterozoic; mainly between 2200 and 1760 Ma
intrusion-dominated magmatic terrane	APei	Syn- to post-kinematic intrusions of granitoid rocks into complex metamorphic terrane	
Superior craton			
Greenstone-granite terrane			
Wabigoon subprovince	Alv1	Arc-like volcanoplutonic sequences; syn- to post-kinematic granitoid intrusions	
Quetico subprovince	Als	Turbidite-dominated metasedimentary rocks (accretionary complex?); granitoid intrusions	Late Archean; volcano-plutonic belts mainly 2750-2695 Ma; Quetico belt 2690-2650 Ma
Wawa-Shebandowan subprovince	Alv2	Arc-like volcanoplutonic sequences; syn- to post-kinematic granitoic intrusions	
"quiet zone"	Alz	Poorly known belt of rocks comparable to Wawa-Shebandowan; regionally retrograded	Syntectonic plutonism, 2688 Ma (unpub. data, Z.E. Peterman)
Gneiss terrane			
Benson block	Amg1	Poorly known terrane composed of gneiss and abundant granitoid intrusions	Middle and late Archean; complex history spans interval 3550 to 2550 Ma
Montevideo block	Amg2	Amphibolite- to granulite-grade gneiss of plutonic and supracrustal derivation; granitoid intrusions	
Morton block	Amg3		

inferred sequence of tectonic accretion

Major structural discontinuities

Malmo discontinuity (Early Proterozoic): Separates supracrustal panels of Penokean fold-and-thrust belt from deeper crustal zone to south

Vermilion fault zone (late Archean): Obliquely cuts and displaces subprovince boundaries within the Superior craton

Great Lakes tectonic zone (GLTZ; late Archean with probable Proterozoic reactivation): Separates high-grade gneissic terranes at southern margin of the Superior craton from classic greenstone-granite terrane of lower metamorphic grade on the north

Appleton geophysical lineament (AGL; late Archean with probable Proterozoic reactivation): Separates Benson and Montevideo blocks in gneiss terranes protoliths. Many of the drill samples from the quiet zone show evidence of late-stage epidote-chlorite-albite alteration, and it may be that the featureless aeromagnetic expression is due in part to a regional episode of retrograde metamorphism in which magnetite was consumed. The faulted margins of the quiet zone could be favorable targets for exploration, but the thick glacial cover in this area (Fig. 2) will make the task both difficult and expensive.

The Archean gneiss terrane of southwestern Minnesota consists predominantly of quartzo-feldspathic gneisses and younger granitoid intrusions that have undergone a long and eventful Precambrian history. Although relatively minor, there are gneissic protoliths of volcanic, pelitic, and iron-formation compositions that may be analogous to greenstone-belt associations and therefore have gold potential. In addition, the gneiss terrane is now thought to consist of three distinct tectonic blocks that are bounded by zones of faulting and ductile shear. These regional shear zones are parallel to the Great Lakes tectonic zone, which is a probable paleosuture between the gneiss terrane on the south and the greenstone-granite terrane on the north. The possibility of finding gold in these shears, perhaps in association with younger Archean and Proterozoic intrusions that range in composition from ferrodiorite to potassic granite, has not been seriously tested.

The Early Proterozoic Penokean orogen of east-central Minnesota is interpreted to consist of an allochthonous fold-and-thrust belt on the southeast and one or more tectonic foredeeps on the northwest. The fold-and-thrust mass includes an internal zone that is mainly gneiss and moderately high-grade pelitic schist permeated by granitoid plutons, and a medial to external zone that is mainly supracrustal rocks of moderate to low metamorphic rank. Deformed volcanic rocks constitute 20 percent or more of the medial zone of the orogen, and the possibility of finding vein-type gold deposits in this environment deserves serious consideration. Exhalative gold deposits in association with iron-formations and massive sulfide lenses are another possibility, as are sedimentary gold concentrations of the Lorrain type in some of the quartzite units with which the volcanic sequences are interstratified. Post-kinematic "Penokean" plutons extend southward from central Minnesota to Iowa, and together with supracrustal remnants appear to form a quasi-continuous belt around the east, south, and west sides of the Archean gneiss terrane. The tectonic and economic implications of this Proterozoic envelope about an Archean core are unresolved and unevaluated.

The Sioux Quartzite is a dominantly fluvial red-bed sequence that rests unconformably atop the Archean gneiss block and its obscure Proterozoic fringe. Sediment was transported chiefly from the northwest, off the stabilized post-Penokean craton, a setting that admits the general possibility for alluvial gold having been deposited in the Sioux. Potentially auriferous source rocks include the Archean greenstone belts and Penokean sedimentary-volcanic-intrusive suites of northern and central Minnesota. Serious exploration of the Sioux is hampered, perhaps fatally, by poor exposure, the generally thick cover of marine Cretaceous strata and Quaternary glacial deposits near basal Sioux contacts, and the extreme resistance to drilling presented by the massive and hard quartzite.

The rocks of the Midcontinent rift system consist dominantly of syn-rifting basaltic flows and intrusions and post-rifting clastic sediments. Prominent among the rift-related intrusive rocks is the Duluth Complex, a very large multiple intrusion that consists dominantly of troctolitic and anorthositic units. The Duluth Complex generally is not an attractive target for gold exploration, although traces of gold have been described in association with base-metal sulfide minerals that occur in the basal contact zone. On the other hand, the complex has attracted considerable attention as a potential source of copper, nickel, vanadium, titanium, cobalt, and platinum-group elements. Non-economic occurrences of these metals have been found in several different rock types and structural settings within the complex, and exploration for PGEs is particularly lively at the present time. Rift-related sedimentary rocks include earlier sequences that are chiefly of intra-rift

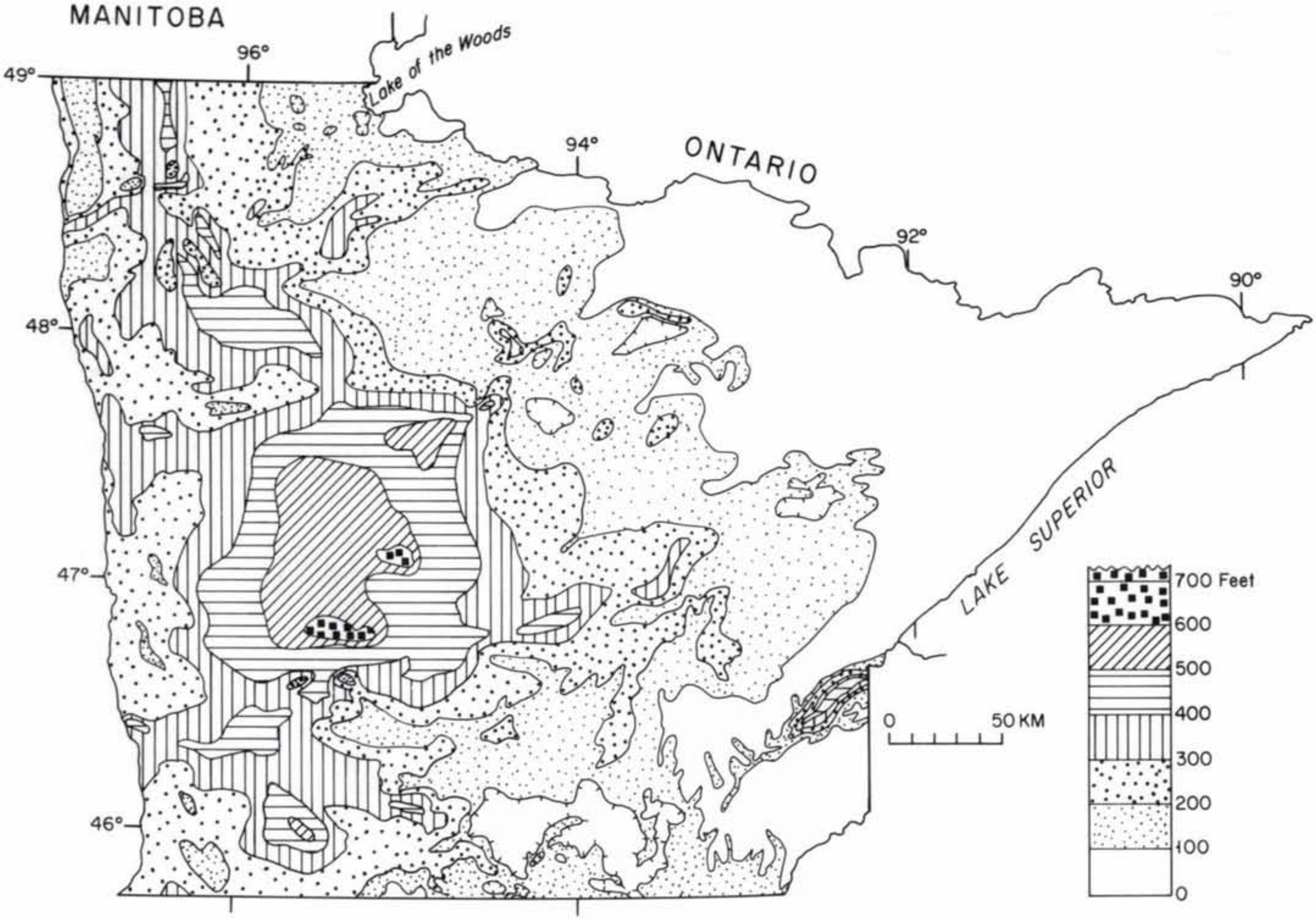

Figure 2. Contour map of glacial drift thickness in northern Minnesota. Contours generalized from published sources and scattered unpublished data in the files of the Minnesota Geological Survey, and are poorly constrained in the west-central part of the map where drift is thickest.

derivation and later sequences that were derived from cratonal sources external to the rift proper. The basins of extra-rift sedimentary rocks that flank and locally overlie the rift axis are potential habitats for alluvial gold deposits, but have never been systematically evaluated.

Exploration for gold or any other commodity in the Precambrian rocks of Minnesota is confronted by the impediment of thick overburden (Fig. 2). The Quaternary glacial deposits are thicker than 30 m (100 ft) almost everywhere in the state except the northeastern quadrant, and thicknesses in excess of 200 m (660 ft) are well documented above the Archean greenstone terrane in the west- and north-central regions. Much of the thickest glacial drift consists of water-saturated sand and gravel. In addition to glacial materials, the overburden in much of the state includes several tens of meters (locally more than a hundred meters) of saprolitic regolith, which developed on crystalline rock during tropical weathering in pre-Late Cretaceous time, and local erosional remnants of poorly lithified Late Cretaceous shale, siltstone, and sandstone. The total thickness of unconsolidated material above sound Precambrian basement, including saprolite, Cretaceous strata, and glacial drift, is routinely greater than 125 m (410 ft) in large areas of western Minnesota, and in places is more than twice that. Successful exploration in the extensive covered areas of Minnesota requires techniques for selecting and characterizing "blind" targets, which, in the case of gold, are likely to be of small horizontal dimensions and thus difficult to resolve.

APPLICATION OF MINERAL DEPOSIT MODELS TO MINNESOTA

G.B. Morey, *reporter*

A mineral deposit model is an accumulation of descriptive data and genetic inferences that characterize the geologic occurrence of a particular commodity. The workshop brought together speakers from a diversity of backgrounds to describe mineral deposit models applicable to Minnesota, and to discuss the value of the model approach in general to effective mineral exploration. This part of the report summarizes the highlights of the workshop sessions, and the appendices contain the abstracts of talks presented by the invited speakers.

In Minnesota, a thick cover of glacial drift inhibits direct geologic observations of the bedrock. This geologic setting requires that remote methods, such as geophysics, and scientific drilling be employed for subsurface mapping and mineral exploration. Mineral deposit models offer a complementary potential for targeting areas beneath the drift for more detailed remote investigations.

As with any strategy for a scientific investigation, however, it is very important to understand the limitations and pitfalls in the use of models. Participants at the workshop fully recognized that models are not panaceas and repeatedly stressed the dangers of simplistic application of mineral deposit models to the complex Precambrian geology of Minnesota.

Samuel Adams (this volume) pointed out that most deposit descriptions, which are the bases or analogs for models, are prepared during and after mining of the deposits. In fact, most of the world's mineral deposits were not discovered by application of sophisticated mineral deposit models, but instead were found by prospecting in areas of known deposits. For a model to have predictive value, it must be based on a reasonably complete deposit description of several examples of a deposit type. Attempts to construct a genetic mineral deposit model may be frustrated, not only by the limitations of existing deposit descriptions, but also by insufficient understanding of geologic processes.

If these caveats about the use of models are well understood, however, models can have applications to areas such as Minnesota, where exploration strategy must involve application of the full spectrum of geologic insight gained from better exposed terranes.

Lode Gold Deposits

Much of the first day of the workshop was devoted to a discussion of the geology of gold, particularly the geology of lode gold deposits in greenstone belts of Archean age. This emphasis was appropriate because Minnesota contains several Archean greenstone belts, but as yet no economically viable gold discoveries.

Approximately 60 percent of the world's cumulative gold production has come from Archean rocks. Of that total Archean production, about 30 percent has been extracted from lode deposits and 70 percent from paleoplacer deposits of the Witwatersrand of South Africa. The Witwatersrand deposits have generally been interpreted as having been eroded from lode deposits, although Hutchinson (this volume) disagrees and suggests an intrabasinal origin involving hydrothermal processes. Mined production from lode deposits has been relatively small in the United States, where most of the gold has been produced from a variety of geologic environments of Mesozoic-Cenozoic age, mostly related to collisional tectonic regimes (Ashley, this volume).

Lode gold deposits account for 65 percent of the total gold production of Canada. Of the remainder, 30 percent is recovered as a by-product from deposits of volcanogenic massive sulfides, porphyry copper, and nickel sulfides, with gold-only production making up 5 percent. Poulsen (this volume) stated that the "central Canadian Shield" contains approximately 75 percent of Canadian lode gold resources. Most of the gold in the Shield occurs in Archean greenstone-granite terranes of the Superior Province, where hundreds of mines have recorded productions ranging from less than 1 ton to approximately 1000 tons of gold. A smaller but nevertheless significant amount of gold has been found in the Early Proterozoic volcano-plutonic rock sequences of the Churchill (or Trans-Hudson) Province. The comparatively small number of gold discoveries in Early Proterozoic greenstone belts of the Canadian Shield may be due to a lower level of exploration activity.

Of particular importance to Minnesota is the fact that the highly productive Abitibi-Wawa greenstone terrane of eastern Ontario extends westward into the northern part of the state. Furthermore, Early Proterozoic rocks of "Penokean" affinity, similar to those that host many of the deposits in the Churchill Province, occupy much of the central part of Minnesota.

Some consideration was given during the workshop to the origin of greenstone-granite terranes. Hoffman (this volume) discussed various models that have been proposed to explain these terranes, and suggested that a model involving accreted island arcs provides the most satisfactory explanation for the stratigraphic, structural, and isotopic attributes of the western part of the Superior Province. The model invokes convergence along subduction zones as a fundamental mechanism. The arcs and other bathymetrically high features are sheared off the subducting slab and are accreted against an evolving craton. This model has several advantages over other proposed models in that it predicts that greenstone-granite terranes should be relatively constant in age along strike, but incrementally older across strike as is observed in the western part of the Superior Province. The model also predicts that greenstone belts should be deformed first by pre-metamorphic thrusting, then by more upright folding, and finally by strike-slip faulting.

Parts of this model have been confirmed by recent Canadian work in geochronology, which shows that in general the last major granitic plutonism in successive greenstone-granite belts of the Superior Province occurred first in the north and is successively younger to the south. These data, together with the moderately north-dipping zones of reflectors near major subprovince boundaries, as shown in the new seismic profiles displayed during the workshop by Richard Sutcliffe (Ontario Geological Survey), imply that successive accretion of volcanic sequences may have been the fundamental process in the growth of the Superior Province.

The productive lode gold deposits in the central Canadian Shield, whether hosted by Archean or Early Proterozoic rocks, are essentially of two types: (1) auriferous sulfide deposits and (2) quartz-carbonate vein deposits. The first type accounts for approximately 20 percent of production and includes many of the more recently discovered deposits. The immense find at Hemlo, Ontario, in the opinion of many, is of this type. The second type has been the mainstay of Canadian Shield production (about 80 percent) and includes such deposits as the Dome and Pamour at Timmins, Ontario.

In the past several years a set of characteristic attributes of the Hemlo deposit has been defined. The immediate host rocks to the ore zone are mostly micaceous schists or highly tectonized rocks of uncertain protolith. The ore-bearing intervals seem to occur in major zones of microcline alteration that in turn are surrounded by sericite schists. The deposits lie in the center of a major zone of ductile deformation that is probably an oblique thrust fault. Earlier formed folds are deformed by shear, and many contacts between rock units are faults or ductile shears. Lenses of quartz and carbonates that locally contain gold cut across metamorphic foliation and shear fabric, and thus imply that the gold was emplaced after metamorphism had peaked. A low-temperature assemblage of antimony and mercury minerals, also emplaced after peak metamorphism, implies that they were formed from earlier higher-temperature minerals, or that the mineralization system was zoned with respect to temperature. Barite also occurs at Hemlo, where it is locally veined or intimately intermixed with gold and with microcline-altered material. Thus many Canadians view the Hemlo deposit as having accumulated at an intermediate to late stage in the deformation history of the area, the mineralization as structurally controlled, and both the alteration and ore-mineral assemblages locally crosscutting layering.

To many Canadians, other auriferous sulfide deposits have attributes similar to those at Hemlo. Most are associated with highly schistose, intensely altered rocks—shear zones—that are inferred to be major structural breaks. Gold-bearing veins occur mostly in greenschist metamorphic domains and are characterized by gold either in disseminated grains or in small irregular patches in quartz. The sulfides include pyrite and arsenopyrite; other minerals are quartz, carbonates, and minor sericite. Fuchsite is present in many major deposits. Associated hydrothermal alteration that commonly includes carbonatization is in places so extensive and pervasive that it may reflect a long period of interaction between carbon dioxide and rock in major hydrothermal systems.

It appears that the difference between the auriferous sulfide deposits and the quartz-carbonate-gold vein deposits are outweighed by features common to both. These features suggest a genetic model that involves late shear-controlled epigenetic processes, although there still is no consensus as to the source or sources of the gold or its transporting fluids.

During the discussions, F.J. Sawkins (University of Minnesota) emphasized that many of the textural and structural features of gold deposits in metamorphosed host rocks can be interpreted in different ways, depending on the conceptual bias of the individual. Therefore he believes the all-embracing structural model for gold ore genesis may not always be entirely applicable. For example, he suggested that the presence of significant amounts of molybdenum and barium and lesser amounts of antimony and mercury implies that the Hemlo deposit may be a somewhat unusual, perhaps new, type of greenstone-hosted gold deposit. In Sawkins' view, the Hemlo orebodies are most closely associated with a quartz-sericite schist unit that contains quartz eyes. This meta-igneous unit and the surrounding metasedimentary formations have undergone extreme flattening and shearing and have been subjected to both regional and contact metamorphism. The situation at Hemlo is thus exceedingly complex, and those inclined to emphasize structural control of most Archean gold deposits have assumed late introduction of the gold into the orebodies.

Careful work on the ore zones and surrounding rocks has indicated crudely symmetrical zones of wallrock alteration around the ore that change from microcline to sericite to an aluminum-bearing silicate (sillimanite-kyanite) outward from the ore zone itself. Textures within them suggest that these alteration zones were initially formed before peak metamorphism and could represent an original epithermal alteration envelope, characterized by a potassium-rich zone associated with the ore and grading to several kinds of argillic zones away from the ore. This concept of an epithermal deposit that has undergone severe deformation and metamorphism fits with the atypical element assemblages seen in the Hemlo ores.

Whatever evolves as the correct genetic model for Hemlo, it should be noted that the ankeritic alteration that characterizes most lode gold deposits is absent, as are any fractures that resemble vein structures. Furthermore, the possibility that reworked epithermal deposits can occur in greenstone belts could be important to exploration strategy.

Regardless of the model chosen, it is of considerable practical significance to the explorationist that Archean lode gold deposits are related to steeply dipping planar shear zones of brittle to ductile deformation that in turn are related to regional faults or regional zones of ductile shear. These regional zones are readily delineated by ground mapping or various geophysical methods, and therefore are obvious first-order targets for gold exploration. The regional shear zones, as wide as several kilometers and as long as several hundred kilometers, are generally subparallel to the stratigraphic succession. Within them, the second-order zones of faulting and intense shearing may be subparallel and relatively continuous, or they may anastomose and enclose "islands" of relatively unstrained rocks.

The structural attributes of lode gold deposits at the property scale are in many respects scaled-down versions of the regional structural geology. Vein systems occur in the central parts of shear zones where rotational or simple shear predominates, but individual veins also may extend laterally into enclosing, less deformed rock where deformation was probably by pure shear.

Gold-bearing vein systems are tabular, subvertical structures. Typically the thickness of a vein system is measured in meters, and its strike and dip dimensions are measured in tens or hundreds of meters. Only parts of a vein system may be economically viable. The vein system in turn may be part of a much larger geologic structure that consists of a system of discrete shears, each hosting its own vein system. As Poulsen (this volume) points out, it is necessary to understand the details of vein geometry and genesis, as well as the regional tectonic setting of lode gold deposits, before an adequate genetic model can be attempted. As often as not, gold will be found in only one particular set of veins, and in exploration probably will be overlooked if temporal and genetic relationships of specific vein sites are not sufficiently well understood.

Similarly, as Sawkins noted, the strong stratabound nature of the Hemlo and perhaps other gold deposits in their present configuration indicates that exploration strategies also require a strong stratigraphic component.

Because the highly productive Abitibi-Wawa greenstone belt in Canada extends westward into Minnesota, it is likely that the vein type of lode gold occurs in Minnesota. However, exploration in Minnesota is difficult because of the mantle of glacial materials. No consensus emerged from the workshop regarding an exploration model or models applicable to the search for buried Archean lode gold deposits in Minnesota. This may mean that there is not a perceived need for a unifying exploration model, that no consensus exists for any given model, or that the participants were not willing to discuss openly the models they favor. Nonetheless, the discussions at the workshop did bring out the importance of a number of geologic attributes that can be used to develop an exploration strategy appropriate to both the public and the private sectors.

Any exploration effort must begin with the delineation of regional deformation zones. This is possibly best done by the public sector utilizing aeromagnetic data recently acquired by the State of Minnesota. Furthermore, it may be possible to recognize more favorable target areas within these deformation zones by identifying segments where the zones have been widened because of local extensional regimes. Many explorationists also believe that gold will be concentrated where shear zones intersect or cut across felsic intrusions; these conditions are recognizable at a regional scale from potential field data.

Publicly supported regional geologic mapping, especially if supplemented by drilling, should be developed to establish temporal and genetic relationships between rock types, structural styles within shear zones, and regional metamorphic regimes. For example, it is now recognized that crosscutting vein and breccia mineralization predominates in terranes of low metamorphic grade, whereas foliation-parallel mineralization is a characteristic of higher metamorphic grades.

On a more local scale, alteration patterns constrained by attributes of the host rock may provide a useful guide. Of particular importance in this regard is the need to identify those segments of deformation zones where microcline alteration and carbonatization have occurred. Here again, however, an understanding of local metamorphic conditions is important because both occur only in areas of low metamorphic grade. Most importantly, the analysis of alteration patterns requires a considerable amount of detailed work and abundant exposures and/or drill holes. Thus the public sector, as well as the private sector, should generate and contribute data that can be integrated in regional interpretations.

At the property scale, two characteristics may assist exploration of a specific target. First, virtually all known ore zones are elongate and plunge parallel to either a stretching lineation or an intersection lineation. Therefore, a careful structural analysis is necessary to any exploration effort. Second, evaluations at the property scale require the careful investigation and documentation of alteration phenomena in the vicinity of possible ore occurrences. It is particularly true at the property scale that an understanding of the systematic interrelationships among host rocks, structures, and alteration phenomena is important to the discovery of gold.

Lastly, the workshop participants recognized that considerable cooperation among various elements of both public and private sectors is essential if gold exploration is to succeed in Minnesota. Very little is actually known about potential gold-bearing rocks because of the glacial drift cover. Thus until recently very little geologic information has been available to test the various recognition criteria that have been proposed for lode gold deposits. As more information becomes available, as exploration proceeds, there will be more opportunities—and incentives—for everyone concerned with exploration to cooperate.

Deposits Of Platinum Group Elements (PGE)

The objective of the second day of the workshop was to provide a genetic framework in which to evaluate the Duluth Complex of northeastern Minnesota as a potential host for economically significant deposits of the platinum group of elements (Os [osmium], Ir [iridium], Ru [ruthenium], Rh [rhodium], Pt [platinum], Pd [palladium]).

Virtually all of the world's PGE production comes from deposits in layered mafic igneous complexes of Precambrian age. The Duluth Complex, though not a perfect analog of the PGE-producing Bushveld, Noril'sk, or Stillwater Complexes, is of sufficient size and petrologic diversity to warrant consideration as a potential PGE producer. PGE distribution patterns in the Duluth Complex are similar to those in several other platiniferous ultramafic/mafic intrusions, in that the PGE occur associated either with chromite-rich units or with sulfides. Weiblen and Dahlberg (this volume) noted that several chrome spinel-bearing stratigraphic intervals in troctolitic rocks contain as much as 7000 ppb (parts per billion) combined Pt + Pd. Similarly Morton and Hauck (this volume) reported anomalous PGE values associated with occurrences of Cu-Ni sulfides in troctolite and gabbro at the base of the Duluth Complex. The highest observed values (1000-3000 ppb Pt + Pd) are associated with higher Cu/Cu +S ratios (>0.4). Although neither PGE occurrence type approaches being of economic grade, the documented presence of elevated PGE makes the Duluth Complex an inviting exploration target.

The average or background platinum content of unmineralized mafic and ultramafic rock is approximately 10 ppb with a range from 0.1 ppb to 500 ppb. In contrast, typical PGE deposits of economic grade may have mean platinum values of 5 to 10 ppm. This implies that the geologic processes responsible for the development of a PGE deposit involve an enrichment factor of 3 or 4 orders of magnitude.

Most geologists agree that PGE originally were introduced into the earth's crust as minor components of mafic or ultramafic magmas. Justified doubts, however, have been expressed by some geologists in regard to the roles played by magmatic and secondary (hydrothermal) processes in the final distribution and location of elevated PGE values. Moreover, although the majority of PGE deposits are thought to be orthomagmatic (i.e., they were fixed in the rocks at the time of their crystallization), considerable disagreement exists as to whether PGE, which are siderophilic, were concentrated by normal magmatic processes producing immiscible sulfide melt (Naldrett and Brugmann, this volume) or by the introduction of hydrothermal (deuteric) PGE-enriched fluids into a crystallizing magma (Stumpfl, this volume).

Magmatic PGE deposits are most commonly associated with stratiform, areally extensive, primary igneous layers that contain some sulfides and oxides, particularly chromite. The ubiquitous association of PGE with sulfide minerals has led to the logical conclusion that economically significant PGE occurrences require the segregation of sulfides into which the PGE preferentially partition. For sulfides to form as discrete phases in areally extensive layers, the solubility of sulfur in the magma must be exceeded more or less simultaneously over widespread areas. Three processes have been proposed to explain this phenomenon—(1) simple cooling and fractional crystallization of the magma; (2) the addition of sulfur from assimilation of wall rocks; and (3) mixing of two magmas, one a primitive PGE-rich composition and the other a more evolved sulfur-saturated composition. The occurrence of PGE-enriched sulfide zones in the Great Dyke of Zimbabwe (Naldrett and Brugmann, this volume) has been explained by simple cooling causing sulfide saturation. Elevated PGE values in the Cu-Ni sulfide-rich lower zone of the Crystal Lake gabbro, Ontario, have been attributed to assimilation of pyritic slates (Eckstrand, this volume). Sulfide saturation caused by mixing of distinct magma compositions is thought by many to have produced the highest grade of PGE deposits in the world—the Merensky Reef (sulfide layers) and the UG-2 horizon (chromite and sulfide layers) of the Bushveld Complex, South Africa, and the J-M Reef (sulfide layers) of the Stillwater Complex, Montana. These deposits contain over 90 percent of the reserves within the principal PGE deposits of the world.

Naldrett and Brugmann (this volume), building on earlier work by Irvine on the origin of chromite layers, have developed the idea that anomalous PGE values in the Bushveld and Stillwater Complexes and in the Great Dyke can be explained by magmatic differentiation and replenishment of a common primary magma. They showed that anomalous PGE values always seem to occur in chromite or sulfide reefs (layers) stratigraphically above the level where plagioclase first appears as a cumulus phase. The observed position of the enriched sulfide-chromite layers is consistent with experimental results, which show that the solubilities of chromite and sulfides in silicate magmas become constant beyond the point where the residual magma has fractionated beyond the cotectic with plagioclase. In the Naldrett-Brugmann variant of the magma-mixing model, the high PGE values occur where such sulfur-saturated residual magmas are replenished and turbulently mixed with PGE-bearing primitive magmas. In developing strategies to explore for PGE deposits formed by the saturation of sulfur in PGE-enriched magmas, Reid Keays of the University of Melbourne and the Geological Survey of Canada recommended geochemical traverses monitoring the stratigraphic variation of sulfur and PGE. He particularly emphasized the utility of the Se/S ratio in pinpointing horizons where magma mixing and sulfide saturation has occurred.

Although Stumpfl (this volume) agrees that magmatic processes are of considerable importance, he noted that the specifics of the ore-forming processes remain unclear. He suggested that volatiles associated with hydrothermal solutions were critical in localizing PGE deposits in many mafic intrusions. He noted that a remarkable feature of the Bushveld and Stillwater Complexes is the occurrence of circular to elliptical areas ranging in diameter from tens to hundreds of meters, where a PGE-bearing horizon departs from its "appropriate" stratigraphic level, cuts downward through the stratigraphic sequence, and finally occurs at elevations as much as 20 m below its original position. These features, termed "potholes," seem to be linked to major tectonic lineaments. The rocks in them are characterized by pegmatoid textures, locally large graphite contents, and concentric alteration halos. The pothole rocks also are characterized by the presence of intercumulus sulfides, associated hydrous silicates, quartz-bearing, high-salinity fluid inclusions, and chlorine in the crystal structures of hydrous silicates, apatite, and graphite. All of these features are consistent with potholes being sites of volatile streaming, which impeded magmatic crystallization. Thus, the potholes appear to be sites where volatiles, which had escaped from the main crystallized magma mass, were concentrated. Because potholes contain some of the highest PGE values, Stumpfl argues that the hydrothermal (probably deuteric) fluids were enriched in PGE by leaching the underlying cumulate pile, and the PGE were redeposited near the crystal-magma interface.

In summary, there is continuing support for the competing hypotheses of magma mixing and volatile influx to explain the major PGE deposits of the world. Like most arguments that involve end-member processes, the truth is probably somewhere in the middle. This point is made clear by the fact that these models are based largely on observations of the same world-class PGE deposit—the Merensky Reef of the Bushveld Complex. Thus, rather than competing hypotheses, it seems more likely that both magma-mixing and volatile-fluxing processes play important, if not in some cases complementary roles in producing economically viable PGE deposits.

It was generally agreed at the workshop that we do not know enough about the Duluth Complex to discount either of the two models in any exploration strategy. It was acknowledged that the Duluth Complex seemingly lacks many attributes found in other platiniferous intrusions, such as large ultramafic units with orthopyroxene and chromite as significant phases and well-developed and areally extensive mineral layering. Historically these differences and the difficulty in identifying discrete intrusions led to a prejudice that the Duluth Complex was not a promising target for PGE exploration. This dogma has been weakened by the discovery of substantial PGE occurrences elsewhere in the world in evolved mafic intrusions similar to the Duluth Complex that lack associated ultramafic units, particularly the Noril'sk.

Indeed, studies of the Crystal Lake intrusion (Eckstrand, this volume), a satellite of the Duluth Complex just north of the International Boundary in Ontario, provides encouraging results in terms of PGE potential of Keweenawan intrusive rocks. The stratigraphy of the northern part of the Y-shaped layered body, which intrudes the argillic Rove Formation, can be divided into two sections that have distinctive textural, geochemical, and mineralization characteristics. The lower zone is characterized by homogeneous olivine gabbro containing disseminated Cu-Ni sulfides. The upper zone is composed of four cyclic units, each grading from Cr-spinel-bearing troctolite and picrite at its base upward to olivine gabbro and leucocratic gabbro. The Cr-spinel-bearing bases of the cyclic units may contain as much as 1-2 g/ton PGE, have Pt/Pd ratios of about unity, and overall have mantle-type geochemical signatures akin to Merensky and J-M Reef deposits. In contrast, the disseminated sulfide ores of the lower zone have geochemical characteristics indicative of assimilation of pyritic footwall argillites and low overall PGE values. Eckstrand suggested that each cycle in the upper zone may have formed by magma replenishment and invoked magma mixing of a primitive magma and an evolved resident magma to explain the PGE enrichment at the base of each cycle.

Morton and Hauck (this volume) have shown that generally low PGE abundances are also characteristic of the the Cu-Ni sulfide-rich troctolitic rocks at the base of the Duluth Complex. Platinum arsenides and Os-Ir-Te alloys have been documented in the sulfide association. Most Pt + Pd values are in the ppb range (200-1200 ppb), with the higher values correlating with high Cu/Cu +S ratios, but Se/S ratios do not correlate well with either Cu/S or Pt + Pd values. As in the Crystal Lake intrusion, the highest grade of PGE identified in the Duluth Complex is a Cr-spinel-bearing olivine-plagioclase cumulate intersected in drill core which yields 7.4 ppm Pt + Pd over a 5-foot interval (Dahlberg, this volume). Further study is necessary to determine if this interval represents a zone of magma mixing. These results suggest that the numerous intrusions that make up Duluth Complex, particularly those displaying evidence of repeated replenishment and differentiation, warrant the level of PGE exploration that thus far has been restricted to the Cu-Ni sulfide-rich basal zone.

To evaluate the potential of hydrothermal PGE mineralization (both magmatic and secondary), Saini-Eidukat (this volume) has investigated possible relationships between PGE and chlorine in several parts of the Duluth Complex. Although he has found no correlation between the two constituents, his work does demonstrate that the introduction of volatiles has affected many Duluth Complex rocks. These results are ambiguous from the ore-formation standpoint because no PGE concentration has been found in the deuterically altered zones.

In general, a consensus was developed that PGE exploration should focus on the search for places where perturbations occurred in the magma system or systems (e.g., the introduction of new magma pulses in evolving chambers). The identification of these perturbations should be aided by geochemical studies designed to establish sulfur saturation levels, Cl/F ratios, abundances of volatile-rich phases, and ratios of PGE to S and to Se. However, much of the Duluth Complex is obscured by a thick cover of glacial materials and the geology is consequently poorly known. Before geochemical exploration can proceed in an orderly fashion there must be improvement in the quality of geologic maps. Such a mapping effort will necessarily involve geophysical modeling and drilling components designed to elucidate relationships between and within individual intrusions. As suggested by Keays, high-precision geochemical profiles involving Pt, Pd, Ir, Cr, Cu, Ni, S, and Se may be of considerable value in any regional exploration program. The possibility of secondary (hydrothermal) deposits should also be considered. As such, attention should also be given to fault zones and veins of pyroxenites and hydrous minerals where volatile-streaming may have concentrated PGE.

Other Deposits

Although the workshop focused principally on lode gold and PGE deposits, the same terranes in Minnesota offer a variety of environments potentially favorable for other kinds of ore deposits. The well-known copper-nickel sulfides in the lower part of the Duluth Complex are a case in point. Similarly, there is a potential for chromium, titanium, and possibly cobalt in other parts of the complex. The economic development of these deposits is more dependent on the development of metallurgical and beneficiation techniques than it is on regional geologic research. Nonetheless, geology remains important because beneficiation must be tailored to specific deposits, and this requires detailed mineralogic and petrologic studies that to date have not been undertaken.

The Archean greenstone belts in northern Minnesota also could be the site of yet another class of gold deposits characterized by an extremely marked stratiform character that is quite distinct from the crosscutting vein aspect of lode gold deposits. F.J. Sawkins noted that a majority of these stratiform deposits occur within siliceous iron-rich rocks consisting of lean, cherty carbonate or silicate iron-formation or their metamorphosed equivalents. As an example he cited the Homestake gold deposits in South Dakota where 1000 tons of contained gold occurs within a thin and possibly discontinuous cherty iron carbonate unit, which in turn is intercalated within a very thick sequence of clastic and volcaniclastic strata. Sulfur, oxygen, and lead isotopic studies, in addition to geologic and mineralogic relationships, indicate that enriched values of sulfur, arsenic and gold in the orebodies must have been essentially in place prior to folding and metamorphism. This does not exclude the likelihood that some of the ore components and associated quartz were redistributed over distances of meters or possibly tens of meters during subsequent deformation. Because of remobilization, most of these orebodies (not all) occur within the crests of complex folds.

Despite these complications, the pronounced restriction of pre-Tertiary gold mineralization in the entire northern Black Hills to the Homestake Formation is strong evidence for an early and thus presumably exhalative origin for the gold mineralization. Some important additional gold deposits that appear to be of the Homestake type include the large Morro Velho deposit in Brazil and the Lupin deposit in the Northwest Territories, Canada. Recent geochemical studies of the Late Proterozoic greenstone belts of Saudi Arabia have confirmed significant gold enrichments in a distal exhalative facies (1-2 ppm Au). There are a number of additional major stratabound gold deposits (e.g., Kular, India; Mt. Magnet, Australia) which differ in many ways from typical lode gold deposits. These deposits are controversial in terms of their genesis, but their essential conformity with local metastratigraphic successions must be considered when exploration strategies are formulated.

The Archean greenstone belts in the northern third of Minnesota also could be the site of a third class of gold deposits where either fracture- or stratiform-related gold may have been liberated from country rock by natural processes involving in-situ weathering. Much of the Precambrian bedrock in the western part of the state was deeply weathered during late Mesozoic time, and that weathering produced a layer of saprolitic clay which in places is as thick as 100 meters. It is interesting to speculate about what a primary lode gold deposit would look like after it had been modified and secondarily enriched by this weathering event.

The greenstone belts in Minnesota also offer a favorable environment for base-metal (copper-zinc) sulfide deposits (Sawkins, this volume). Volcanic-hosted massive sulfide deposits that contain copper and zinc, by analogy with those known in Canada, can be expected to occur at the tops of sequences where felsic volcanic rocks (dacite, rhyolite) are abundant. These deposits, because of the sulfide constituents, are amenable to geophysical exploration, which is essential in a terrane covered by glacial deposits. Sawkins noted that recent research on volcanic-hosted sulfide deposits has shown that they have a genetic connection with underlying felsic magmatic systems. Thus Sawkins suggested that rare earth element patterns can be used to evaluate potentially fertile versus barren volcanic intervals and that consequently this technique should be more widely used in Minnesota.

As with the secondary gold deposits, it would again be interesting to speculate about the size and grade of deposits that would develop where a primary Precambrian sulfide deposit was secondarily enriched by weathering processes. As with secondary gold deposits, the exploration for secondary sulfide deposits should focus in the northwestern third of the state, where chances are better that any ore-bearing saprolite would be preserved.

Another favorable environment for gold and massive sulfide deposits is the Early Proterozoic Penokean orogen in east-central Minnesota. Poulsen (this volume) noted that parts of the orogen have rocks and environments similar to those that characterize the Churchill Province in Canada. Along the same line, Sawkins noted that parts of the orogen have a potential for the presence of sediment-hosted, stratabound, copper-lead-zinc-sulfide deposits similar to those found in the Rammelsberg ore bodies of Devonian age in Germany.

There also is an excellent potential for copper and silver deposits in Middle Proterozoic rocks of the Midcontinent rift system in east-central and southeastern Minnesota. Both native copper and stratiform copper (+ silver) have been found in sedimentary rocks of lacustrine origin in Michigan (White Pine) and Wisconsin. As has been documented many times, such units are pyrite-rich reductants and act as very efficient traps for copper in oxidized, sulfate-rich ground waters. Finally, Sawkins suggests that carbonate rocks of Paleozoic age in southeastern Minnesota may have some potential for Mississippi Valley type lead-zinc deposits. However, Sawkins noted that such deposits in Minnesota are unlikely to be of commercial size and grade because of their distance from probable source-rock sequences in the southern Midcontinent.

Future Directions

It is relatively easy to speculate that, due to its geological diversity, Minnesota probably contains several kinds of undiscovered nonferrous mineral deposits. However, because the bedrock is exposed only in a relatively small part of the state, finding any deposits that there are will be very difficult. Indeed, it is not even possible to consider the full range of deposits that could be found because so much of the bedrock is unknown. Rectifying this situation will require a long-term effort involving geologic mapping and drilling, together with the full range of contemporary geophysical, geochemical, and petrologic techniques. Furthermore, a good understanding of Minnesota's economic mineral potential will come only from integration of so-called practical studies by the exploration community and the state and federal surveys with academic studies in universities.

Because the geology is complex and poorly understood, Adams (this volume) stressed that mineral deposit models should be as simple as possible if they are to be expected to work in the state. Emphasis should be placed on understanding the overall geologic setting that creates favorable environments for ore deposits, rather than on the elaborate minor details that characterize many models. In Adams' view, a high priority should be given to acquiring basic data and ensuring that the data are in a form that will be usable in the coming decades.

Naldrett pointed out the need to understand new deposits within their regional geological contexts. For example, he observed that PGE deposits at Noril'sk in the USSR were in part controlled by regional structures that are similar in some respects to those in the Midcontinent rift system in the United States. He suggested that reflection seismic studies in the North Shore Volcanic Group structurally above the Duluth Complex might be a way of establishing the presence of structural features similar to those at Noril'sk.

Foose observed that good geophysical models for many ore deposits have not yet been developed. Therefore the geophysical signatures of many deposits buried by glacial cover may not be recognized for what they are. In Nevada, the U.S. Geological Survey is evaluating a wide range of geophysical techniques to establish which would be most useful to exploration in the Basin and Range country. Foose suggested that a similar approach would be useful in Minnesota. An example of the usefulness of geophysical data in covered terranes is the work of Chandler, who has used potential field data to prepare a preliminary and interpretive geologic map of the covered central part of the Duluth Complex. This map has yet to be tested by drilling, but this geophysical approach provides a useful starting point for any regional exploration program in that part of the Duluth Complex.

The importance of understanding the difference in regional tectonic frameworks is highlighted by recent work in Canada. There, certain greenstone belts are extensively mineralized, whereas other belts have very few deposits. The difference cannot be explained away as a difference in level of exploration activity. Rather it seems likely that because the individual belts formed at different times, they are fundamentally different tectonostratigraphic entities and for that reason contain different mineral values. In Minnesota, almost nothing is known about chronostratigraphic relationships, either within belts or between belts. These relationships need to be established if exploration is to proceed in an intelligent and systematic manner.

In conclusion, Adams reiterated the importance of doing basic geology, geophysics, and geochemistry if environments in Minnesota are to be compared with environments known to be favorable for deposits elsewhere. However, he also pointed out that nothing would help the situation more than the discovery of a new economically viable ore deposit. He ventured to predict that by the year 2000 there will be at least two new mining districts in Minnesota. Although the identity and location of these districts cannot be forecast, it is reasonable to assume that they will be discovered simply on the basis of the discovery rate for orebodies around the world. Adams challenged the workshop attendees to participate in the acceleration of these discoveries, through accomplishment of the scientific research and institutional coordination that are prerequisites. As he put it, "There will be one or two companies that a year from now, or 3 or 4 years from now, are going to look as bright as Western Mining does for having discovered Olympic Dam, because they are going to come in, they are going to do a couple of really simple things, and they are going to find some orebodies. And everybody else is going to say 'gee, weren't they clever, weren't they focused, weren't they smart to choose those things?' There's going to be an element of luck, and you can't do anything about that. The thing the state can do is to make sure that you focus on the simple things, on the basics for which confidence is sufficiently high that if you use them, the relationships are sound and they are going to lead to mineralization. And get the information out, as quickly as possible, and make sure it's good."

APPENDIX A

PROGRAM

PROGRAM OF THE WORKSHOP ON MINERAL DEPOSIT MODELS APPLICABLE TO MINNESOTA,

held April 3-6, 1989, at the
University Radisson Hotel, Minneapolis, Minnesota

Monday, April 3, 1989 — Ballroom

5:00 - 7:00 p.m.
Registration and icebreaker (cash bar)

Tuesday, April 4, 1989 — Ballroom

8:15 a.m.
Registration

8:30
Welcome
Priscilla C. Grew, Minnesota Geological Survey

GOLD

Co-chairs: Steven A. Hauck, Natural Resources Research Institute
Michael P. Foose, U.S. Geological Survey

8:45
Mineral Deposit Models: Promises and Pitfalls
Samuel S. Adams, Colorado School of Mines

9:15
Gold Sources, Witwatersrand
Richard W. Hutchinson, Colorado School of Mines

9:45
Types and Environments of Gold Deposits of the Western United States
Roger P. Ashley, U.S. Geological Survey

10:15
Coffee break

10:45
Review of Gold Deposits in the Central Canadian Shield
K. Howard Poulsen, Geological Survey of Canada

11:15
Minnesota Overview
David L. Southwick, Minnesota Geological Survey

12:00 noon
Lunch on your own

1:30 p.m.
Gold and the Evolution of the Superior Province: Results from New Research in Ontario
A.C. Colvine, Ontario Geological Survey

2:00
Origin of Granite-Greenstone Terranes
Paul F. Hoffman, Geological Survey of Canada

2:30
Coffee break

3:00
Panel/Audience Discussion on Gold
Moderator: Keith Laskowski, Newmont Exploration, Ltd.
Panelists: Glen Adams, Noranda; Don Kohls, Goldfields; Colvine; Hoffman; Poulsen; Southwick

4:00
TECHNICAL METHODS WORKSHOP

Recognition and Interpretation of Shear Zone Structures
Peter J. Hudleston and Christian Teyssier, University of Minnesota, Twin Cities

5:30
Dinner on your own

7:15
Poster Session (informal conversation, beer keg on tap)

9:00
Adjourn

Wednesday, April 5, 1989 — Humphrey Room

PLATINUM GROUP ELEMENTS (PGE)

Co-Chairs: Steven A. Hauck, Natural Resources Research Institute
Michael P. Foose, U.S. Geological Survey

8:45 a.m.
Origin of PGE Concentrations in the Bushveld, Great Dyke and Lac des Iles Complexes
Anthony J. Naldrett, University of Toronto

9:15
Platinum Deposits: Products of Hydrothermal Processes?
Eugen F. Stumpfl, Mining University, Leoben, Austria

Discussion

10:00
Coffee break

10:30
Ni-Cu PGE Magmatic Mineralization in the Crystal Lake Layered Intrusion, Ontario, and the Fox River Sill, Manitoba
O. Roger Eckstrand, Geological Survey of Canada

11:00
Minnesota Panel on PGE — Duluth Complex
Penelope Morton, University of Minnesota, Duluth
E. Henk Dahlberg, Department of Natural Resources
Paul W. Weiblen, University of Minnesota, Twin Cities
Bernhardt Saini-Eidukat, University of Minnesota, Twin Cities

12:30
Lunch on your own

PGE Occurrences in Australia: Implications for Ore Genesis and Exploration Models
Reid R. Keays, University of Melbourne and Geological Survey of Canada

2:30
Coffee break

3:00
Panel/Audience Discussion on PGE
Moderator: Roger J. Kuhns, BHP-Utah International
Panelists: Craig S. Bow, consultant, Lakewood, Colorado; Dahlberg; Eckstrand; Morton; Naldrett; Stumpfl; Weiblen

4:00
TECHNICAL METHODS WORKSHOP

Significance of Relative Variations in PGE Concentrations in Layered Intrusions
Paul W. Weiblen, University of Minnesota, Twin Cities

5:30
Dinner on your own

7:15
Poster Session (informal conversation, beer keg on tap)

9:00
Adjourn

Thursday, April 6, 1989 — Humphrey Room

FUTURE DIRECTIONS FOR APPLICATION OF MINERAL DEPOSIT MODELS TO MINNESOTA

Chair: Priscilla C. Grew, Minnesota Geological Survey

8:45 a.m.
Beyond Gold and PGEs
Frederick J. Sawkins, University of Minnesota, Twin Cities

9:15
Panel/Audience Discussion on Future Directions and Development of Workshop Conclusions and Recommendations
Moderator: Priscilla C. Grew, Minnesota Geological Survey
Panelists: Adams, Ashley, Keays, Naldrett, Sawkins, Southwick, Stumpfl

10:15
Coffee break

11:30
Concluding Remarks
Samuel S. Adams

12:00
Adjourn

POSTER SESSION

All posters to be on display from 7:15 p.m., April 4, to noon, April 6.

T.L. Klein, W.C. Day, and D.L. Southwick (USGS-MGS)
Mineral Resource and Geologic Studies in the International Falls and Roseau 1° x 2° Quadrangles, Northern Minnesota

Robert J. Horton, Bruce D. Smith, and Val W. Chandler (USGS-MGS)
Geophysical Investigations, International Falls and Roseau Quadrangles, Minnesota-Ontario

Val W. Chandler (MGS)
Aeromagnetic Surveying Program

Mark Jirsa and David Southwick (MGS)
Minnesota Scientific Drilling and Mapping Program

Roger Kuhns (BHP-Utah International)
The Hemlo Gold Deposit

P. Morton, Henk Dahlberg, J. Miller, P. Weiblen, M. Foose (UM, DNR, MGS, USGS)
PGEs in the Duluth Complex

K.J. Schulz, S.W. Nicholson, and W.F. Cannon (USGS)
Metallogeny of the Midcontinent Rift in the Lake Superior Region

Mark J. Severson (NRRI, Duluth)
"Stratigraphy" and General Geology of the Partridge River Intrusion, Duluth Complex, Minnesota

Bruce D. Smith, Robert J. Horton, Val W. Chandler, and Victor F. Labson (USGS-MGS)
Advanced Airborne Geophysical Methods Applied to Geologic Mapping of the Effie-Coon Lake Complex, Minnesota

R.H. Sutcliffe and others (Ontario Geological Survey)
A Reappraisal of the Abitibi Greenstone Belt: New Data from High Precision Geochronology and Seismic Reflection Profiles

P.C. Thurston and others (Ontario Geological Survey)
A Geological Reevaluation of Northwestern Ontario

M.L. Zientek (USGS)
Platinum Group Element-Enriched Sulfides in the Stillwater Complex, Montana

APPENDIX B

ABSTRACTS

MINERAL DEPOSIT MODELS: PROMISES AND PITFALLS FOR EXPLORATION

Samuel S. Adams
Colorado School of Mines
Golden, Colorado

Sit down before fact as a little child, be prepared to give up every preconceived notion, follow humbly wherever and to whatever abyss nature leads, or you will learn nothing.
Thomas Huxley

Geologic characteristics, such as rock and alteration types and anomalous concentrations of certain elements in rocks or soils, are used and observed in exploration for mineral deposits. The characteristics that are chosen are believed to provide some indication as to the presence or absence of a deposit in an exploration area. When such geologic characteristics are used to describe or represent a mineral deposit type and/or predict the location of a new deposit in an exploration area, they are collectively referred to as a "model." Different types of models are composed of and use geologic characteristics and interpretations in different ways; thus it is important that any model be explicitly defined so it is clear what it contains and how it was constructed.

Models that use only factual observations, such as the orientation and amount of displacement on structures, or the gold content of altered rocks, are referred to as *empirical* or *descriptive* models. Models used in the search for new deposits may be referred to as *exploration* models, particularly if they involve information on how the exploration program is carried out. Models that include interpretations of the origin of geologic characteristics of a deposit type are referred to as *genetic* or *process* models.

Empirical models may be as simple as those used by prospectors who sample quartz veins or pan for gold in stream gravels. They may be as complicated as the rock types, structures, alteration types, mineralization styles and other features associated with porphyry copper deposits. *For successful exploration, models should be as empirical and simple as possible and yet provide the desired discoveries.* Empirical models avoid the risk that inaccurate genetic interpretations may lead to the misapplication of geologic characteristics in an exploration program. However, empirical models still require that geologists make judgments as to which geologic characteristics are most useful and important. Most empirical models are influenced to some extent by interpretation, because it is human nature to think in terms of cause and effect. Recent discoveries of Carlin-type gold deposits in Nevada have resulted largely from the application of empirical models that include criteria such as (a) laminated, carbonaceous silty limestones, (b) faults, (c) jasperoids, (d) dikes, and (e) anomalous concentrations of gold and other metals.

In mature exploitation areas, the easier discoveries have been made, and purely empirical models are less able to provide the desired new discoveries. At this point exploration may be terminated or a more effective model developed. The greatest opportunities for more effective models are (a) the identification of new empirical geologic characteristics, (b) new or improved techniques (i.e., geophysical methods), or (c) development of a genetic model that identifies new geologic characteristics and more effective predictions from all the geologic characteristics of the deposit type. Ultimately, the only reasonable options will be to construct a genetic model or terminate exploration. If a genetic model is undertaken it must be remembered that:

1. it may not be possible to construct a sufficiently reliable genetic model for exploration with existing data and understanding,

2. the resulting genetic model may have limited predictive capability and reliability,
3. flawed genetic models commonly result because incomplete and unsystematic modeling methods are used, and
4. we can rarely prove anything in the natural sciences; at best we can only consider the reasonable alternatives, test them, eliminate the less tenable hypotheses, and develop **strong inference** that the surviving hypotheses are correct.

Once a genetic model has been constructed, an experienced explorationist will have to decide if the model is likely to be sufficiently reliable and predictive for use in exploration. If it is not, and if it cannot be improved, one should not hesitate to file it away for the time being.

Development of reliable genetic models for exploration requires, in addition to sufficient and accurate geologic data for the deposit type, modeling methods that protect against our natural tendencies to (a) be satisfied with explanations rather than accuracy in interpreting geologic observations, (b) accept the first or most familiar geologic process to explain geologic observations, (c) defend interpretations and models once they have been developed, even in the face of conflicting data, and (d) consider only one or a few plausible interpretations for geologic observations, thereby decreasing the likelihood that we will have included the correct interpretation.

The following modeling approach is proposed for the development of genetic models that have the greatest potential for reliable predictions in exploration.

Step 1. *Define deposit type.* Identify the dominant geologic characteristics that typify examples of the deposit type and also geologic characteristics that set the deposit type apart from related or similar deposit types.

Step 2. *Compile analog deposits.* Carefully select deposits for which the geologic data are sufficient to demonstrate that each deposit belongs to the deposit type; where doubt exists, deposits should be excluded or the uncertainties clearly noted.

Step 3. *Compile geologic characteristics for analog deposits.* The dominant geologic characteristics of the analog deposits, particularly those useful for interpreting geologic processes and/or at a scale useful for exploration, are systematically compiled in tabular format; suspect data are not included; decisions are made regarding the need to collect missing data and the adequacy of the data base for completion of the model.

Step 4. *Identify formation processes.* All plausible geologic processes that may have formed the geologic characteristics of the analog deposits are identified as the initial step in identifying the process **essential** for formation of the analog deposits **(multiple working hypotheses)**; tests are devised to eliminate the less tenable processes, thereby developing **strong inference** that the remaining processes were essential for deposit formation.

Step 5. *Select diagnostic criteria.* One or more geologic characteristics formed by each essential formation process are chosen for use in identifying in exploration areas whether or not that process operated; since all essential formation processes must have operated for a deposit to have formed, the more processes that can be identified in an area, the greater the likelihood that a deposit is present.

In summary, empirical mineral deposit models are preferred in exploration and resource studies as long as they yield the necessary results. When the results with empirical models are unacceptable, a genetic model may provide the required results, particularly if sufficient well-described analogs and adequate understanding of the geologic processes are available. Blind discovery of the Olympic Dam deposit in South Australia, which contains resources of two billion tons of copper, uranium, gold and silver ore, is a superb example of the successful application of a genetic model in exploration.

RE-EVALUATION OF SOURCE OF WITWATERSRAND GOLD

Richard W. Hutchinson
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Many characteristics make it unlikely that the immense concentration of gold in the Witwatersrand paleoplacer deposits came from a detrital source in an uplifted, deeply weathered and denuded hinterland to the north and west by lengthy transport into the basin. Greenstone-hosted gold lodes appear volumetrically inadequate to supply the gold, and there are geological reasons to doubt the capability of hydrothermally altered granites (HAGS), weathered Archean paleoregoliths, or direct weathering of other Archean rocks to supply it. Nevertheless, there are many similarities between Archean greenstone-hosted deposits and the Witwatersrand ores, and also between the rocks associated with each. Gold of a similar low fineness and high mercury content is found in both types of ore, and both are associated with minor amounts of base metal sulfides. Rounded pebbles of bedded, auriferous pyrite and/or pyrrhotite are abundant in the Witwatersrand ores and, although rare, are also known in some conglomerates with which the greenstone-hosted lodes are closely associated. In the latter, the pebbles have apparently been derived from pyritic/pyrrhotitic sulfide-facies exhalites in the nearby lodes. Three texturally different varieties of pyrite present in the Witwatersrand ores are allogenic pebbles of compact pyrite, allogenic pebbles of porous pyrite, and idiomorphic grains of authigenic pyrite. All three varieties are auriferous, although to differing degrees. Magnetite and ilmenite, the most common heavy minerals in placer deposits, are strangely lacking in the Witwatersrand ores, whereas leucoxene is abundant.

Both the Witwatersrand and the greenstone-hosted ores are associated with geochemically and lithologically similar tholeiitic basaltic and ferruginous sedimentary rocks. The ferruginous sediments in both types of ore have low but definitely anomalous gold contents, and chemical deposition suggests chemical rather than detrital transport of gold. So also does the delicate, algal filament-like texture of gold in the Witwatersrand carbon reefs. Another important but generally unrecognized common factor between many major Archean gold lodes and the Witwatersrand deposits is their similar age. Both are between 2.9 and 2.6 Ga old, whereas other minor paleoplacer gold-uranium deposits throughout the world are either older or younger—a consequence of the worldwide diachroneity of the transition from Archean-like to Early Proterozoic-like tectonic environments.

On the basis of all these relationships, it is suggested that the source of the abundant Witwatersrand gold is endogenous rather than exogenous to the Witwatersrand basin. Pyritic auriferous exhalites were formed along the tectonically active northwestern margin of the basin by shallow marine hydrothermal discharge. This was generated by, and accompanied or very closely followed, the andesitic-basaltic volcanism of the Dominion Group and lower Witwatersrand Supergroup. These volcanic rocks, together with underlying Archean basement rocks, were subsided and buried by marginal down-faulting, and underwent reaction with entrained seawater. This leached them of silica, iron, gold, and minor amounts of base metals and also affected adjacent basement greenstones and granites to form HAGS, thereby generating the hydrothermal fluids in a manner like that described from modern seafloor systems. The auriferous pyritic exhalites were deposited near the basin margin faults where the fluids vented, but these proximal deposits passed basinward into more distal, oxidic ferruginous strata and ultimately into shallow algal banks. They were, however, subsequently detritalized and reworked by fluvio-deltaic

processes along the faulted, regressive margin of the basin to form the quartz-pyrite pebble-rich conglomerate reefs and re-enrich the distal algal banks. Many detrital heavy minerals, including uraninite and perhaps minor gold, were swept into the basin from the eroded hinterland, and this may explain other minor gold-uranium-producing paleoplacer deposits. But magnetite and ilmenite passing through the zone of reducing hydrothermal discharge at the basin's edge were sulfidized to form authigenic, rather than allogenic detrital pyrite, and remnant leucoxene.

Why the Witwatersrand deposits, so similar to Archean greenstone-hosted lodes that formed at about the same time elsewhere on the earth, are so much larger and more productive remains enigmatic. Possible explanations are (1) more efficient mobilization of gold in the more permeable basalts of the Dominion Group due to enhanced water-rock reactions; (2) more effective precipitation of gold due to hydrothermal discharge into a cooler, more oxygenated and platformal organic-rich depository; and (3) prolonged duration of the Witwatersrand activity, which lasted nearly 200 million years—all in contrast to conditions that would have prevailed in a rapidly subsiding, tectonically unstable, basinal greenstone-belt environment.

TYPES AND DISTRIBUTION OF GOLD DEPOSITS IN THE WESTERN UNITED STATES

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Almost 95 percent of the 350 million troy oz (10,900 metric tons) of gold produced in the U.S. since the early 19th century has come from the western conterminous states, and most of the gold reserves and resources of the U.S. are located in this region. Although about 70 percent of world gold production has come from Precambrian terranes, gold deposits in Precambrian rocks have accounted for only about 11 percent of total U.S. production. Instead, the substantial gold resources of the western U.S. are found in remarkably diverse geologic environments.

Low-sulfide gold-quartz veins occur mainly in the Paleozoic-Mesozoic metamorphic belts of California and Oregon. These veins, and placers derived from them, accounted for most U.S. gold production before 1900. Massive-sulfide orebodies containing significant amounts of gold also occur mainly in these metamorphic belts, and they occur in Precambrian rocks of central Arizona as well. The most productive Precambrian deposit in the U.S., however, is the gold-bearing iron-formation at the Homestake mine, Lead, South Dakota, which accounts for about 10 percent of total U.S. gold production. The Homestake has produced gold almost continuously since 1876; from 1945 until 1980, a period of relatively low U.S. gold production, it was the largest U.S. producer.

Polymetallic vein deposits occur around intrusions of both Mesozoic and Tertiary age in the Great Basin, and around Laramide intrusions in Arizona and New Mexico. They also occur around the Boulder batholith of western Montana, the Idaho batholith, the Bald Mountain and Wallowa batholiths of northeastern Oregon, and Mesozoic and Tertiary plutons of northern Washington. Although most of these deposits are small, gold in the extensive placer fields of northeastern Oregon, western Idaho, and western Montana came mainly from erosion of these veins. The most important polymetallic deposits are fault-controlled veins and replacements of carbonate rocks in large districts zoned around porphyry stocks, such as the Tintic district in Utah (3.4 million troy oz production), and the Cove deposit in Nevada (4 million troy oz reserves).

Porphyry copper and copper-molybdenum deposits, in which gold is a by-product of base-metal production, accounted for about 40 percent of U.S. production from the late 1940s to the mid-1970s. The largest gold producer of this type, the Bingham district in Utah, accounts for about 5 percent of total U.S. gold production. Gold-bearing skarn deposits occur in a few porphyry districts, the largest being the Carr Fork deposit in the Bingham district (4.6 million troy oz reserves), and the Tomboy-Minnie and Fortitude deposits in the Battle Mountain district in Nevada (3.4 million troy oz production and reserves).

Exploitation of epithermal veins associated with volcanic rocks began with discovery of Nevada's Comstock Lode in 1859. Epithermal deposits accounted for significant production from 1892 until 1915, and there has been a renewed interest in these deposits in the past decade. Underground mining of high-grade veins, which characterized the early period of production, has largely given way to bulk-mining of lower grade stockworks and replacement orebodies. Epithermal veins and replacements are the most widespread precious-metal deposit type in the western U.S. They occur in early Tertiary calc-alkalic arc rocks of northern Washington; in interior calc-alkalic andesite-rhyolite belts of early to middle Tertiary age in Idaho, central and southern Nevada, western Utah, southwestern Colorado, and southwestern New Mexico; in alkalic centers in central Montana, western South

Dakota, central Colorado, and northern New Mexico; in calc-alkalic andesites of the Cascade arc, especially in the mid-Tertiary part of the arc that extended into western Nevada; in bimodal basalt-rhyolite sequences of middle and late Tertiary age in southeastern California, southern, western, and northern Nevada, southeastern Oregon, and southwestern Idaho; and in late Tertiary and Quaternary andesite-rhyolite fields that formed in the California Coast Ranges near the migrating Mendocino triple junction. The only volcanic terranes lacking epithermal deposits are the flood basalts of the Columbia River Plateau and Snake River Plain and the oceanic basalts of coastal Oregon and Washington. Epithermal deposits were formed at shallow depths in hydrothermal systems driven by subvolcanic intrusions, at temperatures from 220° to 290°C. The hydrothermal fluids, like those of modern geothermal systems, were largely of meteoric origin and generally of low salinity.

Disseminated gold deposits in sedimentary host rocks have attracted considerable commercial and scientific interest since the Carlin mine in Nevada opened in 1965. Most of these deposits are located in the Great Basin. They are largely concentrated in northern Nevada, but scattered deposits occur in central and southern Nevada, western Utah, and southern Idaho. Host rocks, mainly of Paleozoic age, are mostly carbonaceous silty limestones and dolomites. Although they formed at temperatures similar to or lower than those typical of epithermal environments, many of them probably formed from fluids of different isotopic character. No clear genetic connection with igneous rocks has been established. New discoveries of these bulk-minable deposits, especially near Carlin, are responsible for much of the significant increase in U.S. gold production in the past few years, and sedimentary-rock-hosted disseminated deposits now account for more than 60 percent of U.S. gold reserves.

GOLD DEPOSITS IN CENTRAL CANADIAN SHIELD: SHEAR ZONES AND VEINS

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Gold is recovered from a variety of Canadian ore deposits. *By-product* gold accounts for approximately 30 percent of annual production and is recovered principally from volcanogenic massive sulfide, porphyry copper, and nickel sulfide deposits. The remainder comes from *gold-only* deposits, including placers (5%) and lode gold deposits (65%), which are the main source of Canada's gold. The central Canadian Shield accounts for approximately 75 percent of Canada's lode gold resources, and most of this comes from the Archean granite-greenstone terranes of the Superior Province (Table 1) with the Early Proterozoic Churchill Province contributing a significant, but secondary, amount. Of particular importance to the state of Minnesota is the fact that the highly productive Abitibi-Wawa terrane extends westward into the northern part of the state. Furthermore, Early Precambrian "Penokean" rocks, similar to those that host many of the Churchill Province deposits, are known to occur in the central part of the state.

The productive gold deposits in the central Canadian Shield, whether hosted by Archean or Proterozoic rocks, are essentially of two types: auriferous sulfide deposits (Bousquet River, Agnico Eagle, Hemlo) and quartz-carbonate vein deposits (Dome, Pamour, Ferderber). The first type accounts for approximately 20 percent of production and reserves and includes many of the most recently discovered Canadian deposits; because of their occurrence in intensely deformed portions of greenstone belts, there is a lack of consensus concerning both descriptive and genetic models that apply to them. The second type has been the mainstay of Canadian Shield gold production (approximately 80%), and it is generally agreed that the deposits are veins of orogenic, epigenetic origin, even though the source of fluids and gold remains controversial.

The descriptive and genetic characteristics of quartz-carbonate vein deposits are closely tied to the nature of the shear zones that provide a locus of gold deposition in granite-greenstone terranes. These shear zones typically record plastic rock deformation, but also are the sites of brittle rock failure. Two types of veins are commonly developed as a result of the failure: (1) shear veins that are parallel to, and contained by, the shear

Table 1. Gold endowment of Superior Province volcano-plutonic subprovinces

Subprovince	Number of deposits[1]	Production	Production + reserves	Number of large deposits[2]
Abitibi	86 (72%)	120.3 x 10^6 oz (84%)	159.7 x 10^6 oz (85%)	16 (80%)
Uchi	16 (13%)	16.9 x 10^6 oz (12%)	20.3 x 10^6 oz (11%)	3 (15%)
Wabigoon	10 (8%)	4.1 x 10^6 oz (3%)	5.3 x 10^6 oz (3%)	1 (5%)
Sachigo	5 (4%)	0.3 x 10^6 oz (1%)	1.3 x 10^6 oz (1%)	
Other	3 (3%)	0.8 x 10^6 oz (1%)	1.7 x 10^6 oz (1%)	
Total	120	142.5 x 10^6 oz	187.4 x 10^6 oz	20

1. Only deposits with more than 100,000 oz gold production plus reserves are considered.
2. The 20 largest deposits in the Superior Province each represent more than 1.5 x 10^6 oz production plus reserves.

zones and (2) extensional veins that occur at a moderate to high angle to shear zones and that commonly extend beyond the limits of shearing. Examples drawn from the Star Lake deposit, Saskatchewan, the San Antonio deposit, Manitoba, and the Sigma deposit, Quebec, show that vein gold deposits typically comprise complex geometric arrays and networks of component shear and extensional veins. The shear veins occur in brittle-ductile high-angle reverse faults. By way of contrast, subeconomic quartz-carbonate veins in the Mine Centre area near the Ontario-Minnesota boundary occur in strike-slip shear zones. In all cases, vein complexity adds to the risk in drilling gold prospects of this type, but risk can be minimized by sound documentation of vein and shear geometries at an early stage of exploration. Geological surveys can contribute toward this end by mapping and documenting regional and local structures in concert with documentation of the structural and lithological controls of known gold occurrences, no matter how minor they might be perceived to be.

GOLD AND THE EVOLUTION OF THE SUPERIOR PROVINCE: RESULTS FROM NEW RESEARCH IN CANADA

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The Superior Province of Canada hosts hundreds of gold mines, which have recorded production ranging from less than 1 tonne up to 1000 tonnes of gold. All of them occur within large-scale transcurrent shear deformation zones, which were active during the latest Archean. The deformation zones constitute a conjugate set to a NNW-directed Shield-wide compression. Gold camps are localized in extensional structures within the deformation zones. Many of these are pull-apart structures that were the loci of fluvial-alluvial sedimentation, a suite of felsic intrusions, and commonly alkaline volcanism. The localization of gold at all scales, from individual veins to the camp-scale, is attributed to the dilation zones produced by the shear deformation.

Mineralization and attendant wallrock alteration are manifested in many different styles. Both are primarily controlled by the shear deformation, which produced different effects on varied rock types in different metamorphic environments. Brittle, brittle-ductile, and ductile deformation correspond to breccia-style, veining, and foliation-parallel mineralization, respectively. The extent and the style of wallrock alteration vary accordingly. Ambient pressure and temperature during deformation primarily determined the response of the rocks to that deformation, and also the mineralogy of ore zones and alteration. Because these ambient conditions are a function of depth, they are reflected in regional metamorphic mineralogy. Thus observations of more than 30 deposits in various terranes in the Superior Province permit construction of a composite depositional model of Archean gold mineralization. The model represents deposits that were formed at depths from less than 2 km to more than 9 km; the predicted styles of mineralization and alteration are consistent with the observed styles in any specific lithology and metamorphic environment. The consistency of the observations with the model suggests that Archean gold mineralization is one single deposit type.

Gold and the ore fluids were introduced from even deeper and may have been partially transported by ascending magmas. At several widely separated locations, the mineralizing event took place around 2680 ± 10 Ma, at least 20 m.y. after the cessation of greenstone volcanism. The mineralization is somewhat younger than the felsic intrusions, which are spatially associated with many gold deposits. Gold concentration may be, temporally, more closely related to slightly younger, minor magmatism of a more alkaline or a lamprophyric affinity. In the Shield, the timing of the mineralization roughly corresponds with late batholith emplacement and granulitization and accompanying magmatism in the lower crust. Thus, the mineralization, which involves heat and mass transfer, is a manifestation in the upper crust of the widespread cratonization processes in the very late Archean. The latest Archean was the largest metallogenic epoch for this style of mineralization.

ORIGIN OF GRANITE–GREENSTONE TERRANES

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Granite-greenstone terranes are characteristic of, but not limited to the Archean, and their origin remains controversial. Some greenstone belts have been interpreted as collapsed intracontinental rifts, others as continental-margin prisms, and still others as relic island arcs. The Superior Province is the largest, and the western Superior Province the best known, granite-greenstone terrane. It therefore provides a testing ground for genetic models, which have implications for mineral exploration.

The intracontinental rift model for greenstone belts, once widely held, is declining in popularity. The diagnostic deposits of active rifts—alluvial fanglomerate, evaporites, alkalic volcanics—are atypical in greenstone belts. Progressive continental rifting results in a stratigraphic sequence in which fluvial sediments pass upward to volcanic rocks in response to lithospheric thinning. In greenstone belts, fluvial sediments, where present, generally overlie the volcanic rocks. Rifting also fails to account for the intrusive nature of most granitoid rocks associated with greenstone belts and is incompatible with the deformation of greenstone belts, which involves vertical extension and horizontal shortening.

The continental-margin model is seldom invoked, but under Archean conditions of elevated mantle temperatures continental-margin prisms deformed during collision events might resemble some greenstone belts. Idealized prisms evolve from rifts, which subside as an isostatic response to crustal thinning, to become passive-margin shelf and rise prisms, which subside due to thermal contraction of the mantle as it recovers from lithospheric thinning. During collision, clastic sediments are deposited in foredeeps that subside flexurally due to loading by thrust sheets and mountains consequent to crustal thickening. Archean prisms would differ from younger ones in ways that would make them more like greenstone belts. The volume of melt resulting from a given amount of lithospheric stretching is strongly dependent on the ambient mantle temperature. Thus, the Archean rift stage would have more voluminous, less alkalic, volcanism. The depth of thermal subsidence consequent to a given amount of stretching is limited by the equilibrium thickness of the lithosphere. Hence, passive-margin shelf sediments—carbonates and quartzites—might have been relatively thin in the Archean. Foredeeps in the Archean might have been relatively narrow and deep, because flexural wavelength is directly, and amplitude inversely, proportional to lithospheric thickness. Thus, Archean continental-margin prisms might have contained thick rift-stage volcanics, thin passive-margin sediments, and thick foredeep turbidites—a sequence compatible with greenstone-belt stratigraphy. However, the continental-margin model does not account for isotopic evidence that little or no older crust lay beneath the volcanics in such granite-greenstone terranes as the Wawa-Shebandowan belt of the southwestern Superior Province.

The model of accreted island arcs provides the most satisfactory explanation for the lithologic, stratigraphic, structural, and isotopic characteristics of western Superior Province granite-greenstone terranes. According to this model, calc-alkaline volcano-plutonic arcs, built on tholeiitic-komatiitic oceanic crust, and in some cases enclosing slivers of older continental crust (in arcs that originated at continental margins by back-arc spreading—the Japan arc, for example), are sheared off subducting lithospheric slabs at subduction zones, then tectonically thickened and dewatered in accretionary wedges, and finally underplated and intruded by plutonic rocks representing the roots of neoautochthonous magmatic arcs advancing laterally through the deformed complex of accreted arcs and trench turbidites. The model predicts that granite-greenstone terranes should be relatively constant in age along strike but incrementally varying in age across strike, as is observed in the western Superior Province. It also predicts that greenstone belts should be deformed first by pre-metamorphic thrusting, then by more upright folding, and finally by strike-slip faulting—a scenario that has implications for gold exploration strategies depending on the timing of gold mineralization relative to metamorphism and plutonism.

The Minnesota River Valley terrane represents a fragment of old continental crust against which island arcs were accreted to the north in the Archean (at 2.69 Ga) and to the south in the Penokean (at 1.85 Ga). The details of arc accretion differ in the north and south. To the north, multiple arc terranes (Wawa, Wabigoon, Uchi-Sachigo) arrived pre-assembled at the Minnesota margin. The ensuing collision, located at the Great Lakes tectonic zone, terminated the Archean orogenic events in the Superior Province. To the south, it appears that individual arc terranes (Pembine-Wausau and Marshfield terranes in Wisconsin; possibly the Hillman-Little Falls terrane in Minnesota) were accreted successively to the Minnesota margin, located at the Niagara fault zone. The arc-continent collision at the Minnesota margin was the first in a succession of collision events which led up to the accretion of Early Proterozoic crust underlying the platform of the midcontinental U.S. Thus, Minnesota contains probably continental-margin prisms and accreted island arcs of both Late Archean and Early Proterozoic age.

FIELD CRITERIA FOR RECOGNITION OF SHEAR ZONE STRUCTURES

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Deformation in much of the crust is accommodated by discrete movement on faults or by ductile deformation concentrated in shear zones. Faults dominate deformation in the upper part of the crust and are readily recognized where exposed by offset of rock units, slickensided fracture surfaces, and effects of brecciation or cataclasis. Shear zones occur deeper in the crust, often as downward extensions of normal, reverse, or strike-slip faults. Characteristic mesoscopic and microscopic structures are found in the ductilely deformed rocks in these shear zones. They can be used to help identify shear zones and also to determine the sense of shear within the zones. The critical feature of all these structures is an *asymmetry* that is either intrinsic to the structure or results from the orientation of the structure with respect to the foliation. The sense of asymmetry can be related to the sense of shear or vorticity of the deformation. These features allow zones of high ductile shear to be distinguished from ordinary metamorphic rocks.

The structures listed below are some of the best for identifying shear zones and determining sense of movement. Only those that are useful field criteria are included; structures formed by brittle movement are excluded. There are a number of other features that can be used if a microfabric analysis is undertaken using thin sections. More information about these and related structures can be found in a special issue of the Journal of Structural Geology (v. 9, no. 5/6) on shear criteria in rocks.

1. *Lineation.* Parallel to shear direction, but by itself does not indicate sense of shear. Common in highly sheared rocks. In weakly deformed rocks an intersection lineation may form perpendicular to the shear direction.
2. *Sigmoidal foliation.* Increases in intensity as angle between the foliation and the shear zone boundary (SZB) decreases. Common in initially isotropic or weakly anisotropic rocks (granite, gabbro, coarse gneiss) and in soft beds bounded by stiff ones (Simpson, 1986, Fig. 2).
3. *S-C surfaces.* Bands of differential shear fairly closely spaced (mm-cm) formed at relatively early stage of deformation. Common in granitic rocks, generally with lineation parallel to shear direction on C surfaces. S and C intersect in a lineation perpendicular to the shear direction (Nicolas, 1984, Figs. 8-14).
4. *C' surfaces or shear bands.* Developed in rock that previously acquired a strong planar foliation due to very high strain. Usually lineated in shear direction. The intersection of foliation and C' is *perpendicular* to the shear direction (Malavieille, 1987, Fig. 7).
5. *Mica fish and foliation fish.* Mica flakes or lensoid patches of foliation; commonly tilted back "against" the shear direction to form "fish." Commonly associated with shear bands (see above) (Lister and Snoke, 1984, Fig. 5; Simpson, 1986, Fig. 9).
6. *Rotated boudins.* Stiff layers may form pinch and swell, and the swells back-rotate like fish. The swells are separated by shear bands. Massive stiff layers boudinage and the boudins forward rotate (Malavieille, 1987, Fig. 8).
7. *Folds.* Asymmetry of folds in layering/foliation parallel to the shear zone indicates correct sense of shear. Folds in pre-existing layering may or may not show correct sense of shear (Simpson, 1986, Fig. 13).
8. *Sheath folds.* High strain rotates fold axes into shear direction and produces sheath- or cone-shaped folds with closed loop cross sections. 3-D exposure can give sense of

shear—sheath closes in direction of movement with respect to the "flat" part of the same layer (Hudleston, 1986, Fig. 11).

9. *Porphyroclast tails.* Recrystallized edges of porphyroclasts dragged out by shear (Simpson, 1986, Fig. 7).
10. *Bookshelf sliding.* Fragments of fractured megacrysts may tilt forward and slip past one another in an antithetic sense to the imposed shear. Common in feldspars (Simpson and Schmid, 1983, Fig. 9).
11. *En echelon veins.* Extensional veins (commonly quartz or calcite) are common in shear zones, forming at about 45° to the SZB. Once formed, they may rotate and develop a sigmoidal shape (Durney and Ramsay, 1973, Fig. 15).

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CONCENTRATION OF PLATINUM GROUP ELEMENTS IN THE BUSHVELD, GREAT DYKE, AND LAC DES ILES COMPLEXES

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The sulfides of the Merensky Reef and Upper Group chromitites of the Bushveld Complex, the Main Sulfide Zone of the Great Dyke of Zimbabwe, and the Roby Zone of the Lac des Iles complex are characterized by very high concentrations of all of the platinum group elements (PGE), but more normal concentrations of Ni, Co, and Cu in comparison to other magmatic sulfide ores. Campbell and Naldrett (1979) showed that the tenor of a low-abundance trace element, such as a PGE in sulfide, is a function not only of the partition coefficient (D), and of its original concentration in the silicate magma with which the sulfide equilibrated, but also of the ratio (R) of the mass of silicate magma to sulfide involved in the equilibration. Campbell and others (1983) and Naldrett and others (1986) suggested that the turbulent interaction between fresh inputs and resident magma in a layered complex would provide the ideal environment for any sulfide present to develop high values of R, and thus become very enriched in PGE.

Like the Merensky Reef, the Bushveld chromitite layers are very extensive, strata-bound formations that occur at the base of well-defined cyclic units. Unlike those of the Lower Group, which occur in ultramafic rocks, the units hosting the Upper Group chromitites involve plagioclase in addition to olivine and bronzite as a cumulus phase. It is only those chromitites occurring close to or above where plagioclase appears as a cumulate phase that are particularly enriched in PGE, because only these chromitites are enriched in sulfide.

Neil Irvine has shown that the mixing of chromite-saturated primitive magma and more fractionated magma, also chromite saturated, will give rise to a monomineralic chromite cumulate. Figure 1 indicates how the solubility of sulfur is likely to vary in the magma of the Bushveld Complex. On crystallization, an initial magma containing but not saturated in sulfur (A) would become saturated (B) and, with further crystallization, would move down the saturation curve, segregating sulfide. The early sulfides would be PGE-rich, but because of the strong partitioning of PGE into sulfide, the magma would become rapidly depleted in PGE, and sulfides segregating later would be PGE-poor. None of these sulfides would be associated with the base of a cyclic unit. If, at an early stage, when the magma resident in the chamber was still in the bronzite field, a fresh input of A was mixed with a small part of that in the chamber, the mixture would lie on the sulfide-unsaturated side of the curve in Figure 1, giving rise to a chromitite devoid of sulfide and therefore devoid of PGE. On the other hand, if the resident magma had entered the gabbro field (e.g., D), when more A was added the mixture could lie on the sulfur-saturated side (e.g., AD), resulting in a sulfide- and therefore PGE-enriched chromitite, or, if the magma were depleted in Cr, a PGE-bearing sulfide layer such as the Merensky Reef.

In the ultramafic succession of the Great Dyke of Zimbabwe, the uppermost cyclic unit contains several zones of disseminated sulfide mineralization. A number of systematic variations in element concentrations and ratios characterize each of the cycles that have been modeled in terms of simple Rayleigh fractionation of Pt, Pd, and Cu. The favored model of ore formation is that a column of magma tens to hundreds of meters high became saturated in sulfide (for example as when a liquid such as A in Figure 1 reached point B), and sulfides fractionally segregated from this and settled slowly through it to become mixed with bronzite cumulates on the chamber floor. Eventually the segregation ceased due

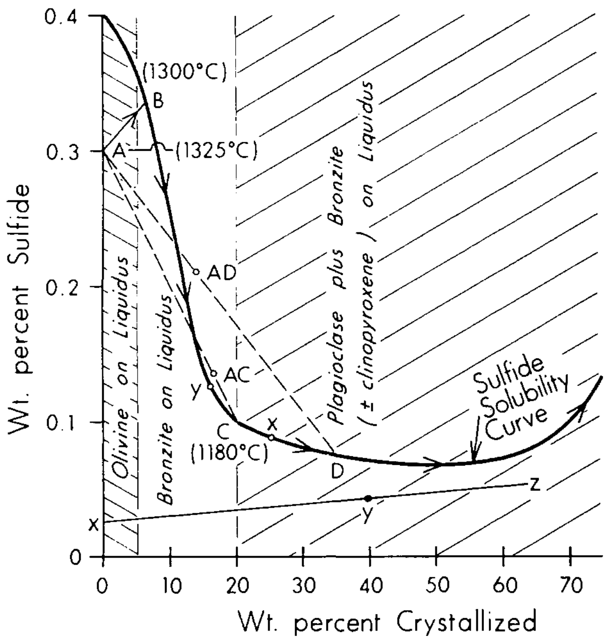

Figure 1. Schematic diagram illustrating variation in the solubility of iron sulfide with fractionation of a chilled margin sample from the Bushveld Complex (see Naldrett and von Gruenewaldt, 1989, for a discussion of the derivation of this curve).

to a fresh input of A pulling the magma off the sulfur saturation curve to the left. At the same time, the input raised the PGE concentration in the magma, which had become very depleted due to the segregation of sulfide. The uppermost (main) zone of mineralization contains too much sulfide to be explained in this way, and it is proposed that the main body of magma became mixed with gabbroic differentiates that had developed on the flanks of the intrusion. This would have tended to pull the mixture into the saturated region to the right of the sulfide saturation curve, and thus have given rise to the segregation of greater than cotectic amounts of sulfide.

The Lac des Iles complex in northwestern Ontario consists of a northern ultramafic and a southern gabbroic part (Sutcliffe and others, 1986). The main PGE ore occurs in the gabbro to the south (Macdonald, 1988). Much of the gabbro is relatively even-textured, shows weak modal layering, and consists of plagioclase, clinopyroxene, and variable amounts of orthopyroxene. It is cut by fine-grained pyroxenitic and also felsic dikes. Large areas within the gabbro have a variable texture. Much of the varitextured area is in fact a megabreccia of gabbroic fragments cemented by a gabbroic matrix. Rounded fragments of both leucocratic and melanocratic gabbro occur in the megabreccia, as do anorthosite fragments. Where it enters the zone of megabreccia, the pyroxenite dike becomes very plastic in appearance, breaking up into a series of deformed fragments. Coarse pegmatoidal and pegmatitic veins cut the varitextured gabbro. In some cases the pegmatite occurs as clots, and in many cases it is sulfide-rich.

Pt and Pd are well correlated and occur in similar proportions in both the gabbroic and ultramafic portions of the complex. Within the ore zone itself, all rock types contain anomalous concentrations of PGE, although the very highest values are normally associated with the pegmatites. Throughout the complex in general, the PGE show a progressive fractionation with the lowest (Pt + Pd)/(Ru + Ir + Os) ratios in the ultramafic rocks, higher ratios in gabbroic rocks, and the very highest ratios in the most enriched samples from the ore zone.

The varitextured zone at Lac des Iles is an irregular zone in the gabbro that is interpreted as having undergone partial melting and remobilization with the formation of igneous breccia, pegmatoids and pegmatites, the deposition of sulfides, and concentration and extreme fractionation of the PGE (Brugmann and others, in prep.). It is proposed that the gabbro body, which contains a small amount of sulfide and associated PGE, underwent remelting due to the introduction of H_2O into largely solidified cumulates. The zone of melting has proceeded, probably upward, through the gabbro. It has been propelled by crystallization at its base, which has provided the energy for the melting at the advancing front. The varitextured gabbro is interpreted as the zone through which the melting front has passed. The pegmatites and pegmatoids are the crystallization products of the melt. As it progressed, the partial melt soaked up the incompatible elements, including sulfide (constitutional zone refining as proposed by McBirney, 1987). Elements such as the PGE, which were associated with the sulfides, concentrated in the partial melt, except those compatible in silicates, such as Ru, Ir and Os, which were removed as silicates crystallized at the base. This led to an enormous fractionation of the PGE and marked increase in the (Pt + Pd)/(Ru + Ir + Os) ratio. Finally, when the partial melt became saturated in sulfide, sulfide remained behind in the residue, and essentially all the PGE in the melt partitioned into this, causing it to become greatly enriched in Pd and Pt, and thus giving rise to the ore deposit.

In summary, Figure 2 shows a section through a hypothetical layered intrusion. In the ultramafic zone, where fresh inputs have occurred before sulfide saturation has been achieved, chromitites occur that are not enriched in Pt and Pd. The onset of sulfide

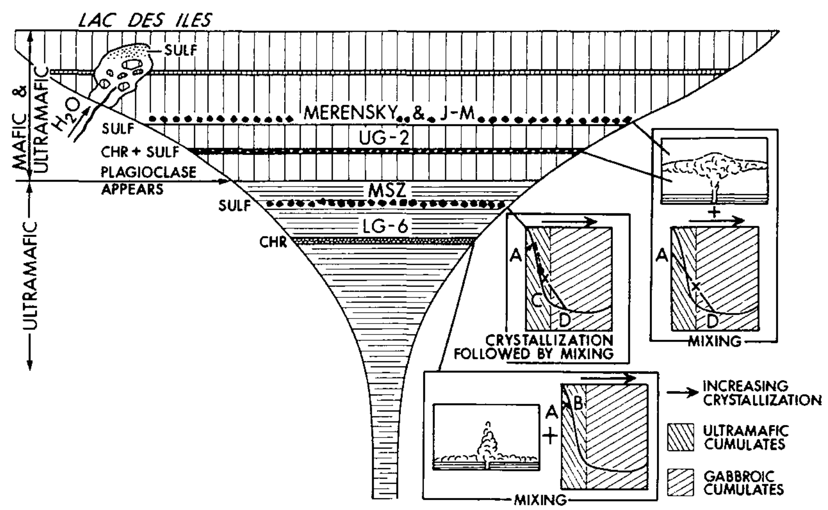

Figure 2. Cross section through a hypothetical layered intrusion, showing the types of chromitite and PGE-enriched sulfide deposits that can result from fractional crystallization, magma mixing, and constitutional zone refining. Mixing of resident with primitive magma before plagioclase has arrived on the liquidus of the former is likely to produce sulfide- and therefore PGE-poor chromitites; fractional crystallization may give rise to a PGE-rich sulfide layer not associated with the base of a cyclic unit; mixing of resident with more primitive magma after plagioclase is crystallizing from the former may give rise to sulfide- and therefore PGE-enriched chromitites or PGE-rich sulfide layers. Volatile-induced partial remelting of cumulates can give rise to constitutional zone refining and the concentration of PGE at the point at which the partial remelt becomes sulfide saturated.

saturation, without magma mixing, can give rise to deposits such as Zones 3 and 2 in the Great Dyke. Once plagioclase has appeared, and the resident magma is on the flat portion of the sulfur saturation curve, a fresh input can cause the resulting hybrid to lie on the saturated side of the curve, forming either a sulfide-bearing and PGE-enriched chromitite, or a PGE-rich sulfide layer such as the Merensky Reef. Finally, the process of zone refining, brought about by volatile-induced partial melting, can give rise to a deposit such as that at Lac de Iles.

PLATINUM DEPOSITS: PRODUCTS OF HYDROTHERMAL PROCESSES?

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Evidence from layered intrusions, ophiolites, metamorphic terranes, and laterites suggests close links between concentrations of platinum group elements (PGE) and the activity of hydrothermal and volatile phases. This is supported by solubility data obtained in the course of experimental studies. There can be no doubt that PGE have originally been introduced into the earth's crust as integral components of mafic and ultramafic magmas. Justified doubt, however, can be expressed as regards the role played by magmatic processes *sensu stricto* in the distribution and final location of PGE concentrations. This is of importance for questions of ore genesis and/or exploration. The purpose of this contribution is to provide an overview of relevant examples of volatile activity from different geological environments with emphasis on results obtained by our group at the Leoben Mining Institute.

1. *Layered intrusions.* A remarkable large-scale feature in the Bushveld and, as initial evidence suggests, Stillwater Complexes is the widespread occurrence of potholes. These are circular to elliptical areas ranging in diameter from tens to hundreds of meters, where the ore-bearing horizon leaves its "appropriate" stratigraphic position, cuts through the stratigraphic sequence, and finally comes to rest at an elevation as much as 20 m below the original position. The distribution of potholes is linked to major tectonic lineaments. Pothole centers are characterized by pegmatoid features, a characteristic PGE mineralogy, occasionally high graphite content, and concentric alteration haloes. Geochemical differences between footwall rocks "below potholes" and "below normal reef" have recently been established. All this points to locally increased intensity of volatile streaming, which impeded magmatic crystallization and thereby formed the potholes.

   On the microscopic scale, widespread association of intercumulus sulfides with hydrous silicates, platinum group minerals (PGM), and quartz-bearing high-salinity fluid inclusions is by no means limited to potholes, but occurs throughout the Merensky Reef. Chlorine is present, not only in NaCl-rich fluid inclusions, but also as a significant constituent of hydrous silicates, apatite, and graphite.

   Similar observations have been reported from the newly discovered platinum deposits in 2.4-b.y. layered intrusions in northern Finland. There, it is of particular interest that PGE-rich layers may or may not be associated with increased sulfide contents.

   Platiniferous clinopyroxenites of the Owendale intrusive complex, Fifield, New South Wales, Australia, show highest PGE concentrations in magnetite- and biotite-rich, base-metal-poor zones. PGM are interstitial to clinopyroxene and some ($PtAs_2$, $PtSb_2$) occur as veinlets in magnetite.

2. *Ophiolites.* Recent results from Troodos, Cyprus, and from Paleozoic ophiolites in the eastern Alps in Austria, reveal complex PGM mineralization associated with chromitites. Laurite (RuS_2) is widespread as inclusions in chromite. Ferrichromite rims and the largely serpentinized silicate matrix carry a wide range of PGM including members of the hollingworthite–irarsite (RhAsS-IrAsS) group, Ir-Cu sulfides, Pt-Ir sulfides, Ru-Fe and Os-Ru alloys, and Rh-Ir-bearing base metal sulfides. All of these are interpreted as products of hydrothermal transport of PGE during serpentinization.

Laser Raman microprobe studies have revealed the presence of pure hydrogen in fluid inclusions in chromites from Troodos. This is considered quantitative evidence for strongly reducing conditions during serpentinization. The widespread occurrence of large (up to 200 μm) inclusions in ophiolitic chromites (clinopyroxene, pargasitic amphibole, tremolite, albite) is of relevance for questions of chromite genesis. There is now evidence that many ophiolites have been exposed to subseafloor metamorphism down to Moho depths, and these processes have also led to extensive mobilization of PGE.

3. *Metamorphic terranes.* The effects of metamorphism on redistribution and concentration of PGE have recently been studied in the Western Gneiss Terrain (WGT), Western Australia, the high-grade metamorphic part of the 2.7-b.y. Yilgarn Block. The WGT extends for about 1000 km in north-south direction along the Indian Ocean coast. It is host to the world's oldest rocks (Mt. Narryer, 4.2 b.y.) and to various remnants of mafic-ultramafic intrusives. One of these, the New Norcia Complex, also known as Yarawindah Brook, consists of olivine-gabbronorites, gabbronorites, and harzburgites; it is of particular interest. PGE values exceeding 1 g/t have been recorded over a 50-m interval of the stratigraphic sequence; grades of 1.5 g/t Pt and 7 g/t Pd occur over small intervals. Additional exploration drilling is currently being undertaken. Sperrylite grains of up to 250 μm in size occur in close association with amphibole, chlorite, and garnet. Strongly fractionated PGE patterns of matrix and disseminated sulfides in the New Norcia body further underline the importance of metamorphic processes for the redistribution and concentration of PGE.

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MAGMATIC NI-CU-PGE MINERALIZATION IN THE CRYSTAL LAKE LAYERED INTRUSION, ONTARIO, AND THE FOX RIVER SILL, MANITOBA

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The Crystal Lake Intrusion, which is a small unmetamorphosed canoe-shaped mafic layered body that is a satellite of the Duluth Complex (1.1 Ga), contains two distinct types of PGE-bearing magmatic Cu-Ni sulfide mineralization. It lies south of Thunder Bay, Ontario, some 40 km ENE of the exposed Duluth Complex, and intrudes flat-lying pyritic siltstone, shale, and argillite of the Rove Formation (Lower Proterozoic), which is correlative with the Virginia Formation of northeastern Minnesota.

The intrusion has a narrow trough-like cross section, plunges gently eastward, and is made up of four main stratiform zones. The Upper Zone (UZ) comprises a medium-grained uniform olivine gabbro with no known sulfide mineralization. The underlying Cyclic Zone (CZ) comprises four cycles of layered ortho-, meso-, and adcumulates totaling about 40 m in thickness. In each cycle, anorthositic gabbro overlies olivine gabbro, troctolite, and 1- to 10-cm-thick Cr-spinel-rich layers, which are typically hosted by olivine-rich adcumulates. The latter have associated anomalous concentrations of PGE and minor Cu-Ni sulfides. The uppermost Cr-spinel layers are planar and continuous, but downward within the CZ, both the degree of synmagmatic disruption of the Cr-spinel-rich layers and the abundance of associated conformable pegmatitic pods increase toward the gradational contact with the subjacent Lower Zone (LZ). The 60- to 90-m-thick LZ consists of an unlayered medium-grained to pegmatitic plagioclase ± olivine orthocumulate, which contains abundant fine-grained cognate xenoliths, and also the disseminated Cu-Ni sulfide mineralization known as the Great Lakes Nickel deposit (45 million tons, 0.34% Cu, 0.18% Ni). Lowermost is the Basal Zone (BZ), a few meters thick and consisting of fine-grained orthocumulate gabbro that contains footwall xenoliths and disseminated and massive low-grade Cu-Ni sulfides. The intrusion of BZ magma hornfelsed and incipiently melted footwall sediments.

Stratigraphic profiles of major element chemistry illustrate the varied compositional character of the layered CZ compared to the other zones. Both Zr and REE contents are significantly lower in the CZ than in the BZ and LZ, which may indicate that the CZ represents new pulses of more primitive magma with correspondingly lower contents of incompatible elements. The mixing of such pulses of new primitive magma with residual evolved magma is also the generally preferred explanation for producing concentrations of Cr-spinel and accompanying sulfides. Zr and Ce contents vary greatly in CZ rocks, but the ratio Zr/Ce is quite constant. In contrast, the Zr/Ce ratio in the BZ and LZ is rather variable. This would be the case if the compositional layering in the CZ resulted from simple magmatic fractionation, whereas the BZ and LZ were affected strongly by assimilation of footwall sediments.

The main zone of Cu-Ni mineralization in the LZ consists of disseminated pyrrhotite-rich sulfides (pyrrhotite, chalcopyrite, cubanite, pentlandite and lesser mackinawite, millerite, niccolite, maucherite, marcasite, pyrite) with which low levels of PGE are associated. Anomalous levels of PGE in the CZ, relative to the rest of the CZ, are spatially related to sparse zones of interstitial Cu-Ni sulfides (chalcopyrite, cubanite, pentlandite, pyrrhotite and traces of bornite, mackinawite, violarite) that are associated with the Cr-spinel-rich layers and are pyrrhotite-poor. The contrasting chemical characteristics of these two mineralized zones shown below demonstrate the more primitive nature of the sulfides related to Cr-spinel layers in the CZ (lower Cu/Ni and Pt/Ir ratios), consistent with their formation by mixing of an evolved and more primitive new magma.

	Disseminated Cu-Ni in the LZ (29 samples)	Cr-spinel associated zones in the CZ (9 samples)
Cu	0.69%	0.039%
Ni	0.36	0.047
Cu/(Cu+Ni)	0.66	0.45
S	3.2	0.14
PGE	1.8 g/t	1.1 g/t
Pt/Pd	1:3	1:1
Pt/Ir	74	46
PGE in 100% sulfide	29 ppm	133 ppm

The total PGE contents are similar in the two types but both the Pt/Pd ratio and the proportion of PGE to sulfide are much higher in the Cr-spinel-associated type, suggesting an affinity to the Merensky Reef type of mineralization as opposed to the Sudbury or Noril'sk types.

Sulfur-isotope values ($\delta^{34}S$) and Se/S ratios of sulfides of the LZ (including the Cu-Ni zone) and BZ (+15.7 ± 1.6 per mil, 86 ± 31 x 10^{6}) closely match those of the pyritic footwall sediments (+15.2 ± 4.3 per mil, 44 ± 32 x 10^{6}). This strongly suggests that most of the S in the Cu-Ni mineralization of the LZ was derived from the sediments, and that this contamination process was critical to the formation of the Cu-Ni deposit. This is supported by correlations among the elements. The PGE (except Os), Au, Ni, and Cu correlate strongly with each other, reflecting their mutual derivation from the magma, but are uncorrelated with S, consistent with derivation of S from a completely separate source.

In contrast, sulfur-isotope and Se/S data for the Cr-associated mineralization of the CZ (+7.0 ± 9.9 per mil, 400 ± 180 x 10^{-6}) are totally distinct, and more similar to mantle values (near 0 per mil, 230 to 350 x 10^{-6}). Hence contamination was not a significant source of S in the CZ, and S saturation was barely achieved on mixing of the magmas. Correlation of elements also is quite distinct from that in the LZ. Os, Ir, Ru, and Rh correlate with Cr, but Pd, Ni, and Cu correlate with S.

Thus two quite distinct zones of PGE-bearing magmatic sulfide mineralization have formed within the Crystal Lake Intrusion by different mechanisms: Cu-Ni sulfides by wallrock S contamination, and the Cr-spinel-associated PGE-rich sulfides by magma mixing.

A rather different genesis is indicated for sparse PGE-rich magmatic sulfides in the Proterozoic layered ultramafic/mafic Fox River Sill (1883 Ma) in northern Manitoba. Sulfur-isotope data ($\delta^{34}S$ = +11.3 ± 3.1 per mil) clearly indicate a crustal source of S in these sulfides. The source is not stratigraphically lower Proterozoic sulfide iron-formation (-0.3 ± 1.1 per mil). Neither is it the same S source as that of sparse magmatic sulfides in coeval Molson Dykes (-0.4 ± 1.4 per mil), which intrude the Archean basement. As in the Crystal Lake Intrusion, the PGE values to date are subeconomic, and the proportion of PGE to sulfide is high. However in the Fox River Sill, crustal S played a significant role in formation of the sparse PGE-rich sulfides.

PRECIOUS METALS IN THE COPPER-NICKEL DEPOSITS OF THE DULUTH COMPLEX

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Large resources of Cu-Ni sulfides found in troctolitic and gabbroic rocks at the base of the Duluth Complex in St. Louis and Lake Counties of northeastern Minnesota are host to substantial reserves of platinum group elements (PGE), Au, and Ag. Analysis of unpublished mining company data showed that weighted averages for combined Pt and Pd values varied as follows: 105 ppb in Water Hen, 378 ppb in Minnamax, 570 ppb at Maturi, 651 ppb at Spruce Road, to a high of 1259 ppb at Dunka Road. Au values varied from a low of 63 ppb at Water Hen to a high of 137 ppb at Spruce Road, and Ag values from a low of 1.22 ppm at Dunka Road to 3.8 ppm at Minnamax (Morton and Hauck, 1987). These distributions were positively skewed and median values are the best estimate of background values. The median values of Pt + Pd for Minnamax, Dunka Road, and Water Hen were 200, 1164, and 103 ppb, respectively.

The largest data base came from the Minnamax area where metal values could be further divided into those that came from Basal and those from Cloud zone sulfides. Basal zone sulfides occur in the lowest 100 m of the Duluth Complex and may be both massive and disseminated. Cloud zone sulfides occur up to several hundred meters into the complex and are usually only disseminated. The median Cu, Ni, and S contents for the Basal and Cloud zones are: 0.90%, 0.25% Cu; 0.19%, 0.07% Ni, and 1.66%, 0.31% S, respectively. However, median Pt + Pd contents are 200 ppb for Basal and 140 ppb for Cloud. It was noted that the PGE contents were enriched in samples that had higher Cu/S ratios.

Subsequent to this analysis of mining company data, detailed logging of diamond drill core was undertaken at Water Hen, Dunka Road, and Filson Creek (Spruce Road area). One anomalous sample previously had been identified at Water Hen and several at Dunka Road (their concentrate values were anomalously high), and logging and sampling were concentrated in areas close to these anomalous samples. Samples from Filson Creek were chosen for PGE analysis on the basis of their known Cu content (company logs) and in some cases the presence of pegmatites.

At Water Hen, the initial company data revealed that of 56 samples, only one was anomalous with respect to PGE, Ag, and Au, and it was related to an orthopyroxenite dike that crosscuts basaltic hornfels beneath the Water Hen intrusion. Subsequent analysis of similar samples by both NRRI and American Shield identified seven more anomalous samples. Detailed logging of these has shown that they are related to (1) orthopyroxenite dikes, (2) mineral graded units 1.5 to 4 m thick from oxide dunite through oxide picrite to troctolite and/or anorthosite that are interpreted to be part of the layered troctolite series (contacts between these layers are sharp and marked by the presence of clinopyroxene and biotite), (3) hybrid rock consisting of basaltic hornfels with minor amounts of crosscutting norite and/or gabbro, and (4) pegmatitic gabbro within the troctolitic series.

Within two different dikes, orthopyroxene varies from En_{54} to En_{56} and two different periods of sulfide mineralization have been identified. The primary assemblage consists of net-textured chalcopyrite/cubanite/maucherite with minor pentlandite and trace pyrrhotite and pyrite. (Note, the typical sulfide assemblage in the Water Hen is pyrrhotite/chalcopyrite/cubanite where pyrrhotite is dominant.) The secondary mineral assemblage consists of chalcopyrite, bornite, and maucherite, minor pentlandite, and trace amounts of niccolite, sphalerite, galena, parkerite, native Ag, native Bi, and tetradymite. Chalcopyrite and bornite consistently replace pentlandite. Chemical analyses of these samples show that they are enriched in As, Bi, Pb, Sb, and Se. The Se/S ratio in one sample is 307×10^{-6}.

At Dunka Road, concentrate values for Pt and Pd were 1176 and 5245 ppb, respectively. The corresponding Cu and Ni contents were 5.11% Cu and 1.41% Ni. The PGE contents are very high for the overall Cu, Ni, and S contents, indicating that the heads for the concentrates would have to average greater than 1000 ppb combined Pt+Pd. The footages that were collected to make up the composite samples for concentrates came from holes located in one part of the orebody. Petrographic work on samples from three of the footages shows that there are two periods of sulfide mineralization: a primary one consisting of pyrrhotite/chalcopyrite/cubanite and/or talnakhite, and a copper-rich secondary period consisting of chalcopyrite, bornite, talnakhite, and maucherite. Pentlandite is replaced by chalcopyrite and violarite.

Also at Dunka Road, a 3-foot intersection of 50% sulfides in DDH 26010 contains 8800 ppb Pd, 1350 ppb Au, and 15 ppm Ag, as well as high values of As, Pb, Sn, Te, Se, Zn, Sb, and Bi. This drill hole is in the same area from which the composite samples for concentrates were collected. The sulfides in this zone are associated with a pegmatitic gabbro consisting of plagioclase, augite, and ilmenite. The upper contact is gradational with highly altered gabbro. Alteration minerals include kaolinite, sericite after plagioclase, chlorite after pyroxene, and numerous crosscutting veinlets of natrolite and analcime. The lower contact is gradational with medium-grained, pyroxene-bearing troctolite that is locally altered to chlorite. In DDH 26028, located 50 m NW of DDH 26010, there is a 17-foot intersection in faulted, altered gabbro that has a concentration of 2800 ppb Pt, at approximately the same elevation as that in 26010. Petrographic work on both sections indicates that both are related to secondary Cu mineralization. In DDH 26010, pentlandite is partly replaced by chalcopyrite, magnetite, and violarite, as well as bismuthinite, native Au, froodite, michenerite, and an unknown mineral with the composition $Pd_7(Sb,Bi)_8$.

At Filson Creek, which is located southeast of INCO's Spruce Road area, anomalously high Pd (700-2200 ppb), Pt (400-900 ppb), Au (100-400 ppb), and Ag (4-4.5 ppm) contents are associated with higher grade copper zones (0.9-1.3 wt%). At least two generations of faulting are evident in the drill core and the Cu and PGE enrichment appears to be structurally controlled along NW-SE fault/fracture zones. Mineralogically, there is a primary period of mineralization consisting of interstitial disseminated chalcopyrite, cubanite, and pentlandite. Pyrrhotite is not present. There is also a very fine grained, secondary mineralization (veinlets and disseminations) consisting of chalcopyrite, talnakhite, bornite, chalcocite, maucherite, niccolite, and an unidentified white/pink highly anisotropic mineral. Se/S ratios in these samples vary from 50 to 1350×10^{-6}; the majority are above 100×10^{-6}. Also, all samples with Pt+Pd contents above 1000 ppb have a Cu/Cu+S ratio of approximately 0.45, whereas the vast majority of samples at Filson have Cu/Cu+S ratios from 0.3 to 0.4.

All samples from areas with high PGE at Water Hen, Dunka Road and Filson Creek seem to be associated with a secondary period of Cu-enrichment. This is supported by all petrographic work and consistently higher Cu/Cu+S ratios (of about 0.45) for samples with high PGE. Se/S ratios analyzed to date indicate either a magmatic source for the sulfur or an unusually high Se content of Virginia Formation.

Access to drill core for these studies was graciously provided by American Shield Corporation, M.A. Hanna Company, USX, and Kennecott.

LITHOCHEMISTRY OF THE PLATINIFEROUS OXIDE–ULTRAMAFIC ASSOCIATION OF THE BASAL ZONE DULUTH COMPLEX, BIRCH LAKE–DUVAL AREA

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The mineralized area is located along the basal contact zone of the Duluth Complex with hornfelsic footwall rocks. The intrusive rocks are a patchwork of gabbroic, troctolitic, and anorthositic bodies, which are subdivided according to Foose and Weiblen (1986) into an older Anorthositic series and a younger Troctolitic series. Descriptions by Wager and others (1969), Bonnichsen (1972), and Dahlberg (1987) reflect the following local stratigraphy, applicable to the PGE occurrence in Duval drill hole DU-15 and its possible continuation to the southeast, as seen in Duval drill hole DU-9.

Sulfide-free rocks having compositions of olivine-bearing gabbro to anorthosite, and olivine gabbro to troctolite, characterize the upper portions of the drill core of DU-15 and rock outcrops in the area. Olivine gabbros and troctolites, however, appear to make up the dominant lithology. The mineral textures are (sub)ophitic with local plagioclase lamination, especially in the rocks having gabbroic to anorthositic compositions.

The sulfide zone (i.e., the basal zone in the strict sense) is characterized by the occurrence of layered olivine-plagioclase cumulates of troctolitic to picritic composition (=mela-troctolite according to Streckeisen, 1973) and intercalations of Biwabik Iron Formation (BIF) or its "metasomatized" (Bonnichsen, 1972) or "digested" (Wager and others, 1969) equivalent. The sulfide zone is poorly exposed, although "magnetite gabbros" have been mapped in the Gabbro Lake quadrangle, which appear to be magnetite-rich (up to 90%) mafic troctolites and picrites. Where the assimilation of BIF is complete, there appears to be a continuous gradation between silicate cumulates and oxide cumulates. Examples of such oxide-rich end members are the platiniferous zones of DU-15 and DU-9. Pegmatoidal intercalations of gabbroic to anorthositic compositions occur in both the sulfide-free and the sulfide zones. The anorthositic compositions, especially, are commonly alkali-feldspar and quartz bearing and may locally grade into quartz monzodiorite with apatite and secondary minerals such as carbonate, biotite, amphibole, and colorless mica. Foose and Weiblen (1986) assume a cyclic alternation of the anorthositic compositions to troctolitic compositions, with the olivine content increasing toward the top of the cycles. This simplified sequence of the major rock types of the sulfide-free and sulfide-bearing zones is complicated and obscured by several categories of hornfelsic inclusions. The inclusions form highly variable concentrations of xenolithic metasedimentary rocks (including BIF), recrystallized olivine-rich gabbro, and troctolite.

Two oxide-rich olivine-plagioclase cumulate sections occur within the sulfide-bearing basal zone. In the lower section (49 feet thick), the PGE zone averages 1.7 ppm with a 5-foot interval containing 7.44 ppm Pt+Pd. The Pt to Pd ratio is about 1:1 (Sabelin, 1986). The upper section (19.2 feet thick) averages 547 ppb Pt+Pd. Apart from chalcopyrite, bornite, pyrrhotite, and pentlandite, Sabelin (1986) reports that the PGMs occur as Pt-Fe alloy, Pd alloys, laurite, irarsite, Pt-sulfur arsenides, and Pd arsenides. Cannon (DNR open-file) also reported ferro platinum and tetra ferro platinum. Studies by Sabelin (1985) on the compositions of the oxides have shown that the major phase is an Fe-rich or magnetite-rich spinel with high TiO_2 (6.01%-11.95%) and variable Cr_2O_3 (3.63%-19.40%), MgO, and Al_2O_3 contents. This major oxide phase is associated with minor amounts of exsolved ilmenite and Al-rich or hercynite-rich spinel (Cr_2O_3 1.66%-22.15%). Tieline plots of the two types of spinel on a Cr/Cr+Al versus Mg/Mg+Fe diagram indicate that these spinels probably originated as a result of unmixing. Interestingly, the tielines F-f and B-b at the top of the diagram represent the highest PGE content of available spinel analyses of DU-15 and DU-9 respectively, reflecting highest Cr/Cr+Al and Mg/Mg+Fe.

The platiniferous zones in DU-15 and DU-9 show a positive correlation of Pt and Pd with Fe_2O_3, TiO_2, Cr, V, and Ni content, and a negative correlation with SiO_2, Al_2O_3, CaO, MgO, Na_2O, K_2O, S, and Cu contents. In addition, samples from DU-9 show negative correlations with P_2O_5 content. Cl displays a steep increase below the PGE zone and appears related to picrite. Occasionally, high chlorine contents (up to 3200 ppm) found in partly serpentinized picrite and oxide cumulates are reflected by rusty-brown, greasy encrustations on drill core. The chlorine appears to be locked in an Fe-Cl-OH phase, occurring in vein-like intergrowths of iron oxides and minor biotite between serpentinized olivine. The nonmineralized oxide-ultramafic associations of DU-6A and DU-14, which are megascopically similar to the mineralized sections of DU-15 and DU-9, appear for the most part to be of pyroxene-rich affinity, and show the same correlations for the major elements and the oxide minerals. However, PGE generally show a negative correlation with the oxide mineral content, and Cu, Ni, and Cl behave in a variable manner.

THE IMPORTANCE OF EVALUATING THE POTENTIAL OF THE DULUTH COMPLEX AS A PLATINUM GROUP ELEMENT RESOURCE

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Patrick J. Ryan, working for Professor Iwao Iwasaki in the Mineral Resources Research Center (MRRC), found the first platinum mineral in the Duluth Complex in 1983 (Ryan and Weiblen, 1984). In addition, a 1-meter, ore grade intersection was found in one drill core by Tatiana Sabelin, also of the MRRC, in 1985 (Sabelin and others, 1986). Since then, indications that the Complex may contain a significant resource of platinum group elements (PGE) have continued to multiply. The information summarized below provides a brief overview of the factors that emphasize the potential significance of the occurrence of PGE in the Duluth Complex.

Currently, the world production of PGE (6.5 million troy ounces [tr. oz] [2.6 Pt, 3.2 Pd] in 1983; 1 tr. oz = 34,286 ppb) comes largely from two sources: the Bushveld Complex in South Africa and the Noril'sk-Talnakh deposits in the USSR (Fig. 1). The very minor U.S. production (6,000 tr. oz, 1983) is from placer deposits and by-product production from copper and gold refining and metal recycling (Lobenstein, 1985). On the other hand, the U.S. consumption of Pt in 1985 was 1.2 million tr. oz out of a total consumption of 2.9 million tr. oz by all market economy countries (U.S. Bureau of Mines, 1986). Projected supply and demand trends indicate that Pt and Pd will be in short supply in the near term (Fig. 2; Christian, 1986).

Future production by 1990 from the Stillwater Complex in Montana is projected at 55,000 tr. oz Pt and 164,000 tr. oz Pd (Wetzell and others, 1985). This production will alleviate but not eliminate the U.S. dependence on South Africa. Furthermore, as illustrated in Figures 3a and 3b, and as is apparent in the projected production figures, the PGE from the Stillwater Complex have a much lower Pt/Pd ratio than those from the Bushveld, and the impact of this on the value of the Stillwater product is uncertain .

The concentrations of PGE in ores from the Bushveld (South Africa), Noril'sk-Talnakh (USSR), Stillwater (Montana), and Duluth (Minnesota) deposits are summarized in Table 1. Assay data indicate that each deposit is characterized by unique PGE relative abundance distributions (Fig. 3). The preliminary assay data on the Duluth Complex indicate that both the Stillwater and Bushveld PGE distributions are present in the PGE occurrences in the Duluth Complex (Figs. 3a-3b). The Duluth Complex mineralization resembles the Noril'sk-Talnakh deposits in general geological setting and in the association of PGE with Cu/Ni sulfide mineralization. The Noril'sk-Talnakh Pt/Pd

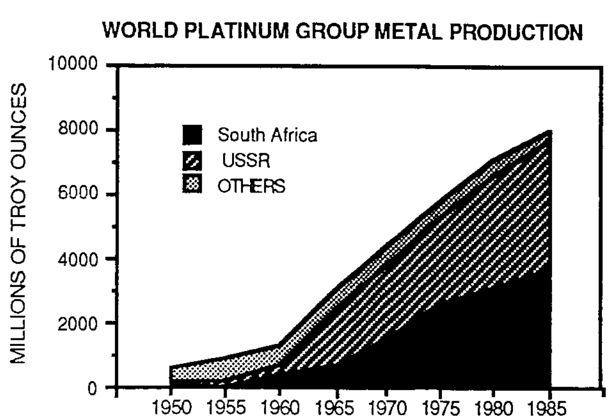

Figure 1. World production of platinum group metals (PGM). Domination of world supplies of PGM by the U.S.S.R. and South Africa has increased steadily since the 1960s. Modified from U.S. Bureau of Mines (1986, p. 96).

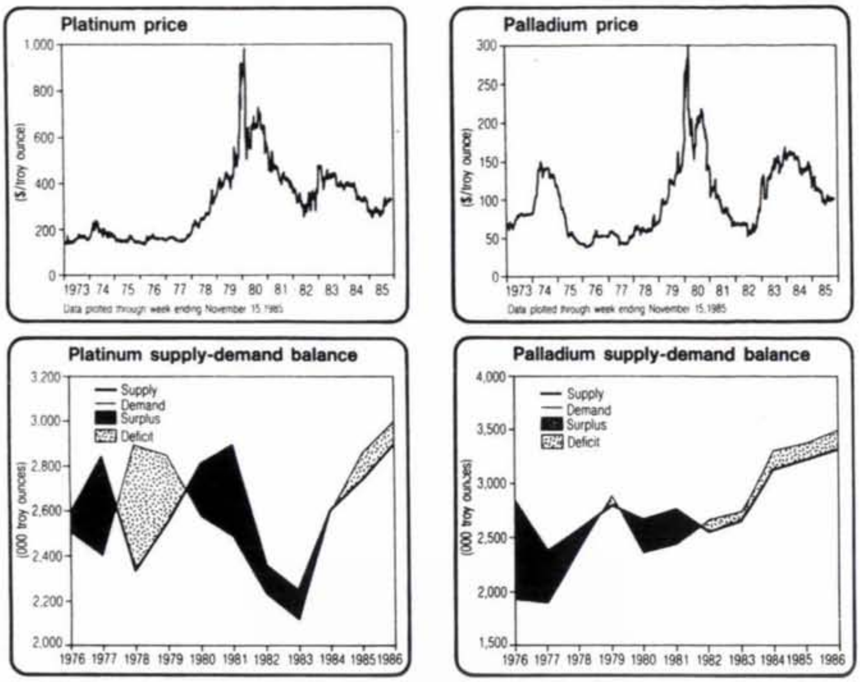

Figure 2. Supply and demand trends for platinum group metals. From Christian (1986).

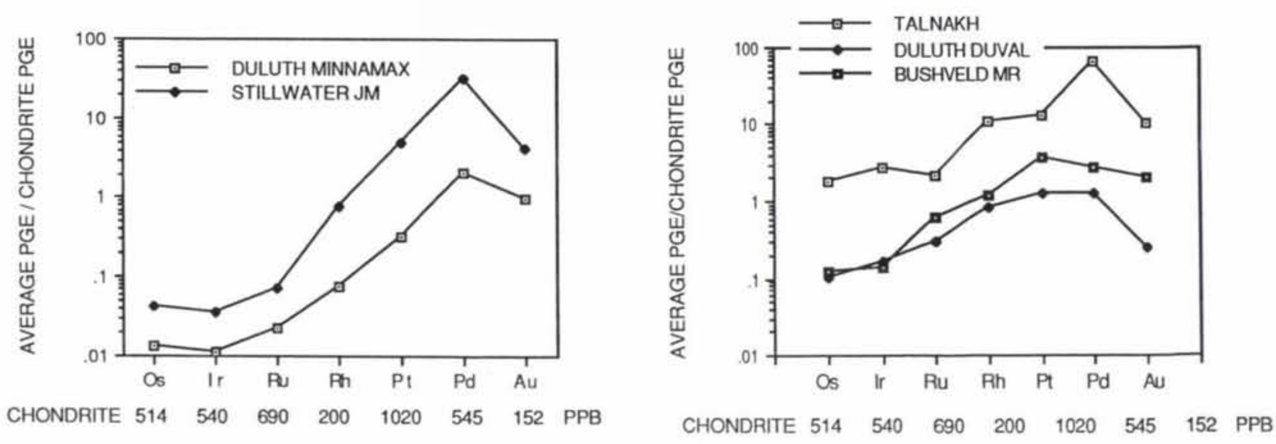

Figure 3. Platinum group element concentrations in different deposits normalized to concentrations in carbonaceous chondrites. Data from Table 1; PGE concentrations in chondritic meteorites are listed on the abcissa of each graph.

Table 1. Concentrations of platinum group elements and gold (in ppb)

	Os	Ir	Ru	Rh	Pt	Pd	Au	Ref
Chondrite	514	540	690	200	1020	545	152	1
Stillwater JM	22	19	50	150	5000	17300	640	1
PGE/chondrite PGE	0.043	0.035	0.072	0.750	4.902	31.743	4.211	
Bushveld Merensky	63	74	430	240	3740	1530	310	1
PGE/chondrite PGE	0.123	0.137	0.623	1.200	3.667	2.807	2.039	
Bushveld UG-2	—	270	—	540	3220	3420	70	1
PGE/chondrite PGE	—	0.500	—	2.700	3.157	6.275	0.461	
Duluth Minnamax	6.6	6	15.3	15.5	333	1113	147	1
PGE/chondrite PGE	0.013	0.011	0.022	0.078	0.326	2.042	0.967	
Duluth Duval	53	88	210	172	1300	710	38	1
PGE/chondrite PGE	0.103	0.163	0.304	0.860	1.275	1.303	0.250	
Talnakh	950	1500	1500	2240	13700	36000	1600	2
PGE/chondrite PGE	1.848	2.778	2.174	11.200	13.431	66.055	10.526	

1. Data from Barnes and others (1985); whole rock concentrations from ore zone rocks.
2. Data from Naldrett (1981); recalculated to reflect PGE concentration in the sulfide fractions.

Table 2. Precious metals assay of flotation concentrates from the Duluth Complex

[From Schluter and Landstrom (1976). Values represent concentrations in ppb *retained* in sulfide fractions *after flotation*.]

Sample	Au	Ag	Pt	Pd	Rh	Ir	Ru
1	1371.4	37714.6	1234.3	4114.3	102.9	34.3	068.6
2	1371.4	51429.0	1028.6	4388.6	068.6	34.3	034.3
3	1371.4	48000.4	0720.0	4182.9	102.9	68.6	137.1

distribution is distinct from the Bushveld and Stillwater distribution, but it could possibly be a mixture of the two distributions found in the Duluth Complex. It is conceivable that the high PGE production from the Noril'sk-Talnakh deposits (Table 1) is a result of empirical knowledge on localization of PGE concentrations in the Cu/Ni sulfide ore gained in the many years of Cu/Ni production.

It appears that the extensive evaluation of the Cu/Ni deposits in the Duluth Complex by INCO, Minnamax, the U.S. Bureau of Mines, and the Copper-Nickel Task Force in the 1970s provides only a cursory evaluation of the PGE resource potential of the deposits. The U.S. Bureau of Mines provided the only published data (Table 2). These data indicate the levels of PGE that could be expected in the Cu/Ni concentrates, but they do not provide any information on what PGE losses were incurred in the concentration process or whether higher PGE concentrations might be found in specific sulfide occurrences: massive ore, disseminated ore, or ore from different stratigraphic and structural settings in the Duluth Complex (Foose and Weiblen, 1986). Apparently the mining companies focused their assay

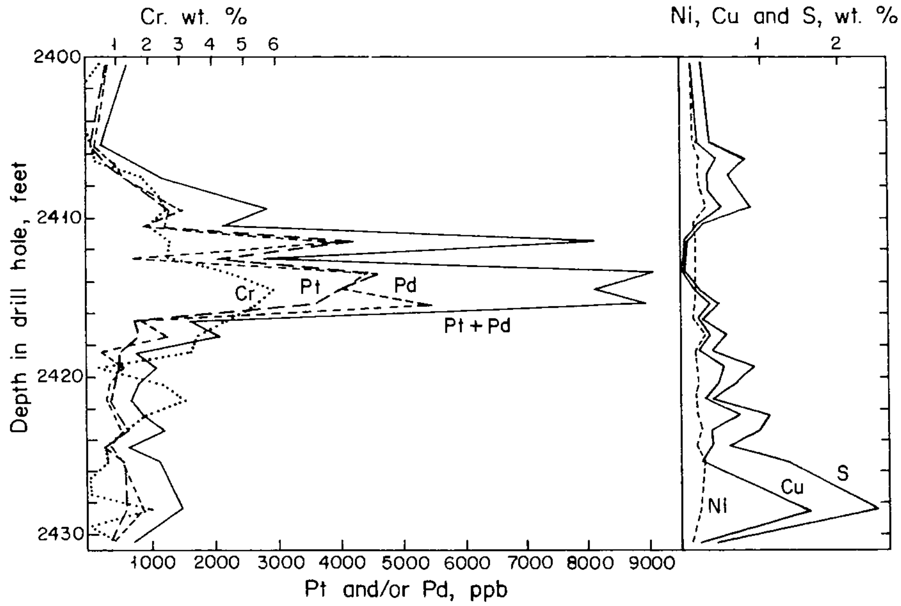

Figure 4. Elemental concentration profile for an interval of Duluth Complex drill core containing a Pt-Pd enriched zone. Note that Pt and Pd do not correlate with S. From Sabelin and others (1986).

efforts on the highest grade *sulfide* ore. It is apparent from new data (Fig. 4) that there are PGE concentrations outside the high-grade sulfide ore.

There are a number of striking differences between the Bushveld and Duluth Complexes in addition to those summarized in Table 1. In particular, the Duluth Complex is characterized by the absence of ultramafic rocks with orthopyroxene as a significant phase, the absence of well-developed and areally extensive mineral layering and stratigraphic successions, and absence of fractionated mineral phases compared to the Bushveld Complex. These differences led to the general prejudice that the Duluth Complex was not a viable target for PGE exploration. However, the discovery of an ore-grade PGE intersection (Fig. 4) has changed that perception. The data summarized in Table 1 and the new data being acquired on the Duluth Complex indicate that there is now justification for pursuing at least three principal exploration targets to evaluate the Duluth Complex as a PGE resource. These are: (1) local concentrations of PGE in Cu/Ni sulfide ore; (2) PGE associated with Cr-spinel-rich rocks; and (3) the possible occurrence of PGE concentrations in anorthositic rocks.

Sufficient information is available on the mineral associations and textures of the three different PGE occurrences enumerated above to guide the search for higher concentrations of PGE in currently available drill core and surface samples. The results of this search will contribute information needed to develop criteria for productive future exploration by geophysical and geological surveys.

It is apparent from the data on mineral associations and textures of the known PGE occurrences in the Duluth Complex that the eventual value of the PGE resource will not only depend on the extent to which high-grade concentrations of PGE are found, but also very strongly on ore recovery processes. For this reason it is important that the mineralogical research directed toward developing criteria for PGE exploration and the research on PGE recovery processes be pursued simultaneously (Sabelin and others, 1986).

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DISTRIBUTION OF PLATINUM GROUP ELEMENTS IN ANORTHOSITIC ROCKS OF THE DULUTH COMPLEX

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The distribution and nature of platinum group elements (PGE) in anorthositic rocks of the Duluth Complex is the subject of a research program at the University of Minnesota, in association with Dr. Paul Weiblen of the Department of Geology and Geophysics, Dr. Gust Bitsianes of the Department of Civil and Mineral Engineering, both at the University of Minnesota, Minneapolis, and Dr. Michael Glascock of the Research Reactor Facility at the University of Missouri, Columbia. These rocks are being studied as part of an overall survey of the potential for PGE concentrations in the Duluth Complex.

To date, most PGE exploration has been concentrated in troctolitic rocks of the Duluth Complex; anorthositic rocks have been ignored. However, geologic relationships suggest that primary or secondary concentrations of PGE in anorthositic rocks may exist. Perhaps more importantly, the examination of PGE *distributions* in these rocks will provide important petrologic clues to the geochemistry of PGE and will constrain models of the formation of the Duluth Complex, much as the use of trace-element and rare-earth-element modeling has done (Weiblen, this volume).

As previously described by Weiblen and Morey (1980), the Duluth Complex does not have an internal structure defined by persistent lithologic layering. However, anorthositic and troctolitic rocks constitute two major intrusive series, which are distinguishable by textural and mineralogical features observable in outcrop. Anorthositic series rocks have been sampled at the interface with various troctolitic units at Duluth, in the Gunflint area, and in the Hoyt Lakes–Kawishiwi area. Petrographic and SEM characterization of these samples show that the principal sulfide minerals are chalcopyrite, pyrrhotite, and pentlandite, with chalcopyrite the predominant sulfide phase. These minerals occur as three main textural types: interstitial void-filling, inclusion, and fine-veinlet textural types, and are similar to those observed in troctolitic series rocks (Weiblen and Morey, 1976), except for modal amounts. Sulfide grain sizes in anorthosites range from <10 micrometer-size inclusions in plagioclase to interstitial void-filling crystals up to 0.5 mm in diameter. The typical sulfide content of these sulfide-bearing rocks is usually only a few tenths of a percent, although a few samples contain up to about 2 volume percent sulfide. As in the troctolitic rocks, sulfide grains can be found in association with hydrous phases such as biotite. This association and the observed textures suggest that the sulfides formed during crystallization of intercumulus sulfide-silicate immiscible melts in the anorthositic rocks. Discrete PGE phases have not been identified in anorthositic rocks.

Anorthositic rocks analyzed for PGE by the nickel-sulfide fire assay/neutron activation method contain Pt and Pd values which range from below detection limits to 50 ppb Pt and 80 ppb Pd. Ir values are between 0.16 and 0.7 ppb. Figure 1 shows the range for chondrite-normalized whole-rock PGE in anorthositic rocks and the Minnamax and Duval deposits. Preliminary data indicate that Pd/Ir ratios in anorthositic rocks are less than 100; i.e., that the chondrite-normalized PGE profiles for anorthositic rocks are relatively flat. To date, the PGE-bearing fraction in the anorthositic samples has not been concentrated to a sufficient degree to obtain above background values for all six PGE. Mineral separates analyzed for PGE show that most plagioclase separates are below detection limits, although one plagioclase separate that contains minute sulfide inclusions contains

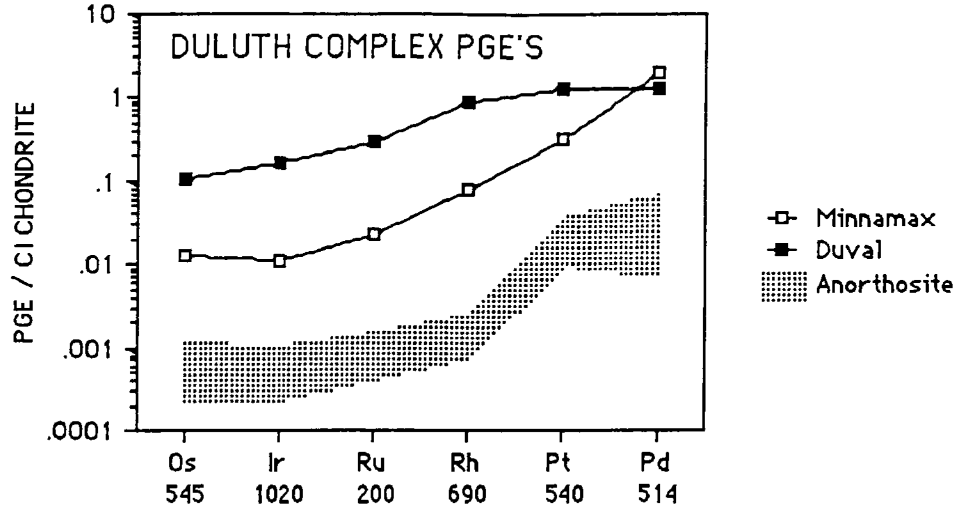

Figure 1. Platinum group elements in Duluth Complex rocks. Whole rock values are normalized to Cl chondrite abundances (shown below each element). Stippled area is range of preliminary data for anorthositic series rocks.

about 50 ppb Pt. The mafic separates (i.e., the intercumulus material) can contain up to 350 ppb Pt.

Different amounts of mineral fractionation is one explanation for differences in Ir depletions found in Duluth Complex rocks. Miller's (1986) model for the formation of the anorthositic rocks involves the fractionation of olivine and pyroxene at depth, from a mantle source with a presumably flat PGE pattern. As interpreted from the chondrite-normalized patterns, it appears that the PGE in anorthositic rocks reflect a fractionation process intermediate between two processes: one that produces a pattern similar to the Minnamax deposit, and one that is distinctly flatter, at the Duval deposit.

Recent studies of minerals such as apatite, micas, and amphiboles by various workers (Ballhaus and Stumpfl, 1986; ; Boudreau, 1988; Boudreau and others, 1986) have shown that hydrous minerals associated with ore zones from the Stillwater and Bushveld Complexes are anomalously enriched in chlorine compared to those from the PGE-barren Skaergaard and Kiglapait intrusions. This and other data have led these authors to conclude that the late-stage fluids that affected the lower parts of the Stillwater and Bushveld Complexes were Cl-rich, and that Cl-bearing fluids may have been a transporting medium for PGE. Figure 2 plots wt.% Cl vs. the molar Fe/(Fe+Mg) ratio, from Duluth Complex, Bushveld, and Stillwater biotites. Two distinct trends, overlapping at low Cl values, can be distinguished. In this plot, all Skaergaard and Kiglapait data would plot below 0.2 wt.% (Huntington, 1979; Nash, 1976).

In both sets of data the influence of increasing fractionation to the right can be seen, but the slope of each trend is different. The difference in slope could represent different bulk distribution coefficients (K_d) for each system, with the bulk K_d being *greater* for the Duluth Complex. A higher bulk K_d for the Duluth Complex could be due to its being a more hydrous system than the other intrusions, and thus crystallizing more biotite. The exponential increase of modal proportion biotite in the Duluth Complex toward the contact with the country rock (Weiblen and Morey, 1980) may be evidence of the hydrous nature of the system.

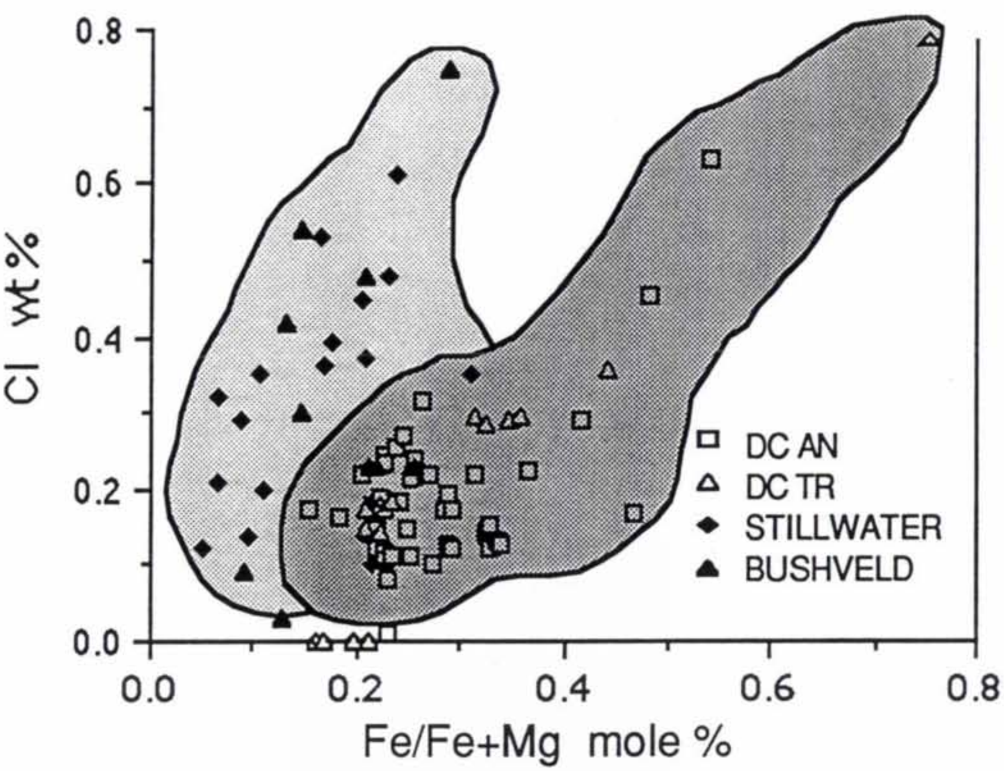

Figure 2. Wt% Cl vs. molar Fe/(Fe+Mg) in the Duluth, Stillwater, and Bushveld Complexes. Stillwater and Bushveld data from Ballhaus and Stumpfl (1986) and Boudreau and others (1986). DC AN = Duluth Complex anorthositic series; DC TR = Duluth Complex troctolitic series rocks. Two trends can be distinguished: one for Duluth Complex samples and one for Stillwater/Bushveld samples.

Of course, a higher bulk K_d could also be due to other factors. It is well known that the Cl distribution coefficient varies in biotites with the Fe/Mg ratio, and also with temperature, fo_2, and f_{Cl}, and possibly with pressure. With the Duluth Complex directly underlying its own volcanic pile, and from evidence such as exsolution textures in pyroxenes, the pressure at crystallization may have been much less than in other intrusions.

Despite the evidence for the presence of Cl in Duluth Complex magmas, we have no data that indicates a direct link between the record of volatile reactions and the occurrence of PGE. Rocks containing high Cl values (up to 3000 ppm) have been found in serpentinized rocks in the Partridge River and Water Hen intrusions in the Duluth Complex (Dahlberg, 1987). This is indirect evidence that Duluth Complex rocks were subjected to flushing by Cl-bearing fluids during or after serpentinization. Rocks from these drill cores contain very low PGE concentrations. Higher than background PGE values found in surrounding rocks (Dahlberg, pers. comm.) could indicate that Cl-bearing solutions leached serpentinized rocks of their PGE and deposited them elsewhere. A major problem with conjectures like the above lies in the controversy over which conditions chloride-complexing will be an important transporter of PGE. Hydroxy and bisulfide complexing may also need to be investigated as possible transporters of PGE in the Duluth Complex.

At this point the geological, textural, and PGE data lead me to conclude that the PGE contents in the anorthositic rocks were the result of a fractionating process intermediate between those which produced the different PGE distributions observed in troctolitic rocks (Fig. 1), but which also resulted in increased Cl contents in biotites with fractionation.

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SOME THOUGHTS ON THE POTENTIAL FOR BASE METAL ORE DEPOSITS IN MINNESOTA

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Despite the current emphasis on precious metal deposits as exploration targets, the potential for discovery of important base metal ores in Minnesota deserves discussion. In my view two distinct types of base metal deposits can be anticipated in Minnesota: copper-zinc deposits in Archean greenstone belts, and stratiform copper deposits in Keweenawan sedimentary rocks. There is also perhaps some potential for sediment-hosted zinc deposits in Animikie basin sedimentary rocks. All are stratabound and extensive—a significant concern in poorly exposed terranes where the drill must be used in relatively early stages of exploration.

Copper-zinc volcanic-hosted massive sulfide deposits, by analogy with those known in Canada, can be expected to occur in association with felsic volcanics (dacites, rhyolites) at the top of volcanic sequences. Recent research work on massive sulfide deposits of this type is increasingly demonstrating that they have a direct genetic connection to underlying felsic magmatic systems. This inferred geochemical coupling has potential in exploration terms, as has been demonstrated in REE patterns for ore-associated versus barren felsic volcanics in many localities and throughout the geologic time scale. Wider use of geochemical discriminants to evaluate potentially fertile versus barren volcanic intervals should be made in Minnesota.

The Proterozoic Animikie basin has potential for the presence of sediment-hosted massive sulfide deposits. This is not the typical rift setting known to be the tectonic framework for most sediment-hosted deposits, but the general setting has similarities to the Rhenische Schieferberger of Devonian age in Germany, which contains the important Rammelsberg orebodies.

There is also excellent potential for the occurrence of copper (+ silver) deposits related to the Midcontinent rift system. The voluminous mafic volcanic rocks of this system are copper-rich and have spawned both native copper and stratiform copper deposits to the northeast in Wisconsin (White Pine) and Upper Michigan. The critical exploration target here, I believe, should be lacustrine paleoenvironments within local equivalents of the Oronto Group. As have been documented in many parts of the world, such units are reduced and pyrite-bearing and act as efficient traps for copper in oxidized (sulfate-rich) ground waters. The large size of deposits of this kind in other rift environments, and the essentially flat-lying attitude of the rift-related sediments in Minnesota that may contain them make such deposits viable targets for carefully planned wildcat drilling.

Finally, the Paleozoic carbonate rocks in southern Minnesota have some potential for the occurrence of Mississippi Valley-type deposits. However, such deposits are unlikely to be of the size and grade to merit exploitation because of their distance from probable source basins.