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ABSTRACTS

MAGMATIC SULFIDE FIELD CONFERENCE IV

PRESENT STATE OF KNOWLEDGE CONCERNING IRANIAN OPHIOLITES AND THEIR METALLOGENIC ASPECTS

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Ophiolitic rocks are widely exposed in different structural units of Iran. They are mainly of Mesozoic age, but some are Paleozoic. The Iranian ophiolite complexes correspond more or less to the normal crosssection of oceanic crust and upper mantle; they show a *mélange* character in some places. Both ocean-ridge character and island-arc affinity are found in different paleogeographic situations and geotectonic settings.

The most important metallic ore related to these ophiolitic suites is chromite, which is mainly exposed in the Esfandagheh–Fariab area (south-central Iran). Petrological studies concerning the origin of the chromite mineralization show that processes of rhythmic layering and subsequent metamorphic differentiation and brittle deformation are the main factors explaining the concentration and displacement of the chromitite layers and chromite bodies in this area (Sabzehi 1983). Preliminary investigations of the occurrence of platinum-group elements indicate that the average concentration of Pt, Pd and Rh is low and similar to that in other alpine-type ultramafic complexes. Recently, some evidence of disseminated sulfide minerals, (*e.g.*, pentlandite, pyrrhotite and chalcopyrite) have been reported from the same ophiolitic zone (Khoi 1982), but they are still under detailed investigation.

The most important nonmetallic ores found in these rocks are asbestos, talc and magnesite, although occurrences of vermiculite, sepiolite and huntite are sporadically found. These minerals bear a close relationship with metamorphosed and metasomatized, serpentinized peridotitic rocks. The host rocks of the main asbestos deposit (cross-fibre chrysotile) in eastern Iran (Hajat mine) consist of serpentinized harzburgite. A petrological investigation of the asbestos deposits in eastern Iran indicates that the asbestos was formed as a result of syntectonic metamorphism caused by the reactivity of the serpentinite when the ophiolitic suite was emplaced during the middle to late Alpine orogeny. Talc and soapstone deposits occur in strongly altered ultramafic rocks (central and northeastern Iran). They were mainly formed during the final stage of alteration and retrograde metamorphism. Magnesite is essentially found in association with highly altered and weathered serpentinized peridotite. The most important deposits of magnesite occur in the ophiolitic belts in central and eastern Iran. Surface water containing carbon dioxide penetrated down through the serpentinized fissures, converting the serpentinite to magnesite and other minerals, such as huntite.

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COMPUTER-ENHANCED STRUCTURAL INTERPRETATION OF THE BASAL SERIES, MOUNTAIN VIEW AREA, STILLWATER COMPLEX, MONTANA

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The Mountain View area of the Stillwater Complex is a triangle-shaped block bounded by two high-angle reverse faults: the Lake fault and the Bluebird thrust. The Mouat nickel–copper prospect, which lies within this structurally complex area, is penetrated by over 110 diamond-drill holes, 88 of which are vertical and were used in this study. The stratigraphic and fault-intersection data from each hole were computerized and used in conjunction with and constrained by the surficial geology to create a three-dimensional representation of the geology of the Mountain View area that can be graphically displayed.

Major northwest-trending faults are nearly vertical and show left-lateral strike-slip movement. Older east- and northeast-trending faults, which appear to be high-angle normal and reverse faults, have displaced the north side upward. These faults subdivide the Mountain View area into a series of contiguous fault-bounded blocks. The sequence of stratigraphic units contained within these blocks consists of (from the top down) the Peridotite zone of the Ultramafic series, the Basal series, metasedimentary rocks intruded by dykes and sills associated with the Stillwater intrusive complex, and unintruded metasedimentary rocks. On the basis of the asssumption that the Ultramafic series – Basal series contact was horizontal at the time of emplacement, the displayed orientation of this contact represents the degree of rotation in each of seven contiguous fault-bounded blocks. Other observable and measurable features include the amount of offset between blocks or movement along faults and the apparent variability in thickness of these stratigraphic units.

THE BORDER RANGES MAFIC–ULTRAMAFIC COMPLEX OF SOUTHERN ALASKA: EVOLUTION OF A VERY LARGE, SULFIDE-POOR MAGMATIC BODY

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In contrast with most intensively studied mafic–ultramafic suites (*e.g.*, Stillwater, Duluth, La Perouse), the Border Ranges mafic–ultramafic complex (BRUMC) apparently contains little magmatic sulfide. Consequently, characterization of this body may help in understanding the factors that help create magmatic Cu–Ni–PGE orebodies. The BRUMC is an elongate, discontinuous zone of plutonic rocks about 1000 km long and 2 -10 km wide in south-central Alaska. Based on field, petrographic, K–Ar, fossil, and compositional data, we interpret the BRUMC as the deep mafic cumulates of the Jurassic Talkeetna Formation (andesitic arc volcanic suite). The 2- to 3-km-thick ultramafic sections are largely composed of dunite ± chromitite, wehrlite, clinopyroxenite and websterite. The 4- to 7-km-thick gabbroic sections are largely composed of gabbronorite (with up to 10–15% magnetite) with lesser gabbro and troctolite. Layering in the BRUMC is dominantly E–W striking and steeply dipping; despite complications due to Tertiary and Recent faults, a more-or-less complete section from ultramafic rocks to ferrogabbronorite is exposed. Detailed field mapping and compositional data indicate 1) long-lived, discontinuous magmatism, 2) both cumulate and noncumulate layering, 3) continuous but repeated evolution of mineral compositions from ultramafic to mafic rocks, 4) evidence for extensive contamination of magmas by sulfide-bearing country rocks, and 5) partial melting of country rocks.

Despite several years of intensive mapping at intermediate (1:24000) to detailed (1:240) scales, geochemical sampling, and geophysical studies, very little magmatic sulfide has been found in the complex. Exceedingly small amounts of pyrrhotite- and chalcopyrite-rich, Ni- and PGE-poor sulfide accumulations have been discovered with the chromitite horizons in cumulate dunites and in troctolitic horizons within the layered gabbroic sequence. Virtually all the sulfide-stained zones examined to date, however, are composed of base- and precious-metal-poor, postmagmatic, pyrite–chlorite–epidote alteration of gabbroic rocks, possibly related to convective circulation of seawater. That the calcalkaline, island-arc character of the BRUMC is not in itself responsible for the absence of sulfide is indicated by the fact that at least

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one other island-arc complex, the Acoje, Philippines, does contain large amounts of magmatic sulfide. Critical features of other sulfide-bearing complexes, *e.g.*, evidence for magma mixing and contamination by sulfide-bearing country rocks, are present in the BRUMC as well. We speculate that the lack of sulfides may be due to (a) the absence of strongly reducing agents in the wall rocks that enclose the BRUMC, and (b) possible inhomogeneities in the abundance of sulfur in the upper mantle below the BRUMC.

THE EFFECTS OF METAMORPHISM UPON THE MINERALOGY, TEXTURES AND GEOCHEMISTRY OF THE KAMBALDA NICKEL ORES

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The Kambalda nickel ores have been extensively modified by metamorphic processes; the ores represent variably deformed and altered magmatic sulfides. Mineralogical layering in banded pyrrhotite-pentlandite massive ores and small foliated pyrite lenses indicate that these ores are laminated blastomylonites that formed in response to shear stress parallel to the ore lenses. The pyrite lenses probably represent deformed magmatic pyrite. Massive sulfides record all deformation events and did not revert to monomineralic *Mss* at peak metamorphic temperatures, although some fabrics may be obliterated by annealing. Matrix and disseminated ores do not display the same fabric elements as massive ores and have been retextured by metamorphic recrystallization and new mineral growth.

Oxidation and sulfurization reactions during metamorphism resulted in contrasting styles of alteration in massive ores compared to matrix-disseminated ores. In low-tenor massive ores (8 to 10% Ni in 100% sulfide–oxides), pyrrhotite typically is altered to pyrite at the margins of ore lenses, whereas significant proportions of pyrrhotite throughout matrix-disseminated ores are altered to magnetite. Continuing oxidation of the ores can result in sulfur-poor pyrite–magnetite–millerite assemblages, especially in high-tenor ore surfaces. These alteration reactions caused considerable variation in the metal-to-sulfur ratio within the ore zone, but metal-to-metal ratios remain unchanged.

GEOCHEMISTRY OF THE KAMBALDA IRON–NICKEL SULFIDES: IMPLICATIONS FOR SULFIDE–SILICATE PARTITIONING MODELS

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Geochemical data from 72 sample profiles through eight Kambalda ore surfaces of contrasting composition and geological settings indicate that there is considerable variation in chemistry both between and within ore surfaces. Within an ore surface, matrix and disseminated ores have a high metal-to-sulfur ratio (2.0), whereas massive ores have a lower ratio (1.6); Fe/Ni shows little variation. Fe/Ni varies markedly between individual ore-surfaces; Ni in 100% sulfides plus oxides can range from 8 to 22%. Kambalda ore surfaces define a suite of compositions in which all elements, except sulfur, increase in abundance as Fe decreases; sulfur values remain constant. Diverse compositions within ore surfaces are interpreted to be due to metamorphic alteration. Ore surfaces of contrasting Fe/Ni value are hosted by geochemically similar komatiites; Fe/Ni does not correlate with the style of metamorphic alteration. The wide range of Fe/Ni values is a feature common to all Western Australian komatiite-hosted Ni deposits.

Gross variations in sulfide–oxide compositions are due to variable $f(O_2)$ values in the sulfide–silicate system prior to eruption. Increasing $f(O_2)$ oxidizes Fe^{2+} to Fe^{3+} in the silicate magma, reducing the Fe^{2+} available for partitioning to sulfide. Octahedrally co-ordinated sites in the magma are also reduced, such that chalcophile elements are more strongly partitioned to sulfide. Variable sulfide mass or degree of fractionation fail to explain the geochemical variations in Kambalda ore, indicating that $f(O_2)$ is the most important control on sulfide compositions in komatiite-hosted deposits and may influence compositions in other types of deposits.

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THE RELEVANCE OF CHROMITE AS A PETROGENETIC INDICATOR IN METAMORPHOSED KOMATIITIC ROCKS AND ASSOCIATED Ni ORES

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Chromite interpreted as an igneous relic is an important accessory in metamorphosed Archean komatiitic ultramafic rocks and associated Ni ores in Western Australia. In relatively Mg-poor komatiitic dunites (olivine $<Fo_{91}$), euhedral cumulus chromite coprecipitated with olivine on the liquidus. In more magnesian dunites (Fo_{92-95}), higher liquidus temperatures prevented the crystallization of chromite until the liquid had cooled by about 300° C; in these rocks, chromite only occurs as a rare, coarse-grained lobate intercumulus phase between adcumulate grains of olivine. In spinifex-textured komatiites, chromite is normally highly skeletal, but euhedral to slightly skeletal grains are common in olivine-rich cumulates at the base of these flows. These crystallized from residual intercumulus liquids, and probably coprecipitated with a Mg-poor (Fo_{90-86}) rim on strongly zoned olivine with a core composition of Fo_{95}.

The composition of the chromite has been extensively modified by metamorphism in all but very low-grade environments. The core of grains lost Al, Mg and some Cr, and the magnitude of the loss parallels metamorphic grade. A rim of secondary magnetite on relict chromite grains becomes thicker and more Cr-rich with increasing metamorphic grade, resulting in homogeneous chromium-bearing magnetite grains in medium-grade domains. In composition, these overlap with ferrochromite from Fe–Ni sulfide ores. The previous interpretation of ferrochromite as a relict igneous phase that crystallized directly from a sulfide–oxide melt is now considered equivocal.

INTERACTIONS OF SULFIDE-SATURATED BASALTS WITH PtFe AND PdAgFe ALLOY CAPSULES: EXPERIMENTAL OBSERVATIONS

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Experimental investigation of the phase relations of selected Columbia River basalts has shown them to be saturated with (Fe,Ni,Cu)S liquid even when the basalt is 95–100% liquid. These experiments were conducted in Pt and $Pd_{50}Ag_{50}$ capsules that had been presaturated with iron. The composition of the PtFe alloys in contact with silicate and sulfide liquid are 83–88 wt. % Pt, 17–12 % Fe. The PdAg capsules have an inner layer of composition 75–80% Pd, 5–15% Ag and 10–15% Fe. Textures and compositions observed in experiments in Pt capsules suggest that the PtFe alloy and sulfide liquid coexist stably over a wide range of pressures and temperatures (3–20 kbar, 1150–1270° C, with $f(O_2)$ approximately that of the MW buffer). No sulfur is lost from the silicate liquid to the capsule, implying that PtS is not stable at these conditions. The concentration of Pt in the sulfide liquid ranges between 0.1 and 0.2 wt. % at 1175–1270° C. Below 1175°C, the level of Pt is below the limit of detection, which is 0.1 wt. %. The Pt content of the blebs in the centre of the charge is the same as that of blebs next to the capsule wall.

The PdAgFe alloy is not stable in the presence of sulfide liquid, but reacts with it to produce a liquid having the composition 75–55% Pd, 20–40% Ag, 2–3% Fe and 4–5% S. Textures observed, including wavy inner-capsule walls and blebs in various stages of necking off the walls, plus the spherical shape of the metallic blebs, demonstrate that the capsule wall was actually melting at the conditions of the experiments (1100–1150°C, 1.5–7 kbar).

Notable features of these results are: 1) Pt and Pd behave differently in the presence of sulfide liquid, 2) they tend to form separate phases from the sulfide liquid, and 3) the valence state of Pt and Pd in the phases in which they are concentrated is zero (Pt) or very low (Pd). Thus both elements are strongly siderophile at near-liquidus conditions. This behavior raises the possibility that Pt and Pd are present in the

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*Speaker.

silicate liquid as native elements. If so, they should tend to behave like colloids rather than trace cationic species. Whatever the valence state of Pt in silicate melts, its concentrations in sulfide liquid coexisting with PtFe alloy are equal to (or less than) the Pt content of sulfide inferred for certain Pt deposits (0.14% Pt in the J–M Reef of the Stillwater Complex, 0.6% Pt in the UG–2 Reef of the Bushveld Complex). The observed values of the ratio Pt/sulfide in these horizons suggest that some of the Pt in them was precipitated in a second phase, possibly a PtFe alloy.

CHARACTERISTICS OF CENTRES OF ARCHEAN KOMATIITIC VOLCANISM, EXEMPLIFIED BY LITHOLOGIES IN THE AGNEW AREA, YILGARN BLOCK, WESTERN AUSTRALIA

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Irregularly distributed elliptical zones of thickening within semicontinuous komatiitic volcanic sequences constitute the ultramafic hosts to those nickel deposits previously categorized as the Intrusive Dunite-Associated class of the Yilgarn Block of Western Australia. Lateral and vertical transition from the thick pods of layered olivine-rich fractionates into genetically related sequences of komatiitic volcanic rocks characterizes the spatial distribution of lithologies in these ultramafic complexes. Textural variations from coarse olivine adcumulates through orthocumulates to varieties of bladed olivine rocks reflect changes in the cooling history of komatiitic liquids; their spatial distribution permits the reconstruction of centres of Archean komatiitic volcanism.

The central dunitic zone of thickening at the metamorphosed Agnew deposit is elongate north–south parallel with the enclosing ultramafic stratigraphy. Remnant igneous and interpreted metamorphic textures, and compositions of associated rocks, document a gradual change from olivine adcumulate in the core into laterally equivalent komatiites. These characteristics are in keeping with the above generalized description of this class of deposit. The Agnew complex can now be interpreted as an Archean volcanic centre or an infilled zone of fractionation such as an actively evolving and periodically replenished lava lake within a paleogeographically flat, dominantly sedimentary environment upon which pulses of relatively thin, laterally extensive volcanic sequences have been spilled. This interpretation seriously questions the validity of a distinction between nickel deposits of the Kambalda (Volcanic Peridotite-Associated) and Agnew types based solely on the intrusive or extrusive nature of the ultramafic host-rocks.

REE VARIATIONS ASSOCIATED WITH THE J–M REEF, STILLWATER COMPLEX, MONTANA

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REE data for seven samples of cumulus orthopyroxene and twenty of cumulus plagioclase from the Banded series are consistent with magma mixing as a fundamental process that produced cyclic units associated with the J–M Reef. The association of the J–M Reef with plagioclase-rich cumulates having

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an order of crystallization different from that observed in the Ultramafic series suggests that a geochemically different type of magma may have been added to the chamber. Such magma may have been characterized by high Al, a $(Ce/Yd)_n$ ratio of 3.7, a $(Nd/Sm)_n$ ratio of 1.5, and a $(DyYb)_n$ ratio of approximately 1. This magma was most likely derived by partial melting of a source of tholeiitic composition in the upper mantle or lower crust. The plagioclase-rich nature of this new magma indicates that it may have been saturated with respect to sulfur even though sulfur concentration would have been low.

REE data for minerals from the Ultramafic series suggest that magmas parental to this part of the complex were derived by multistage dynamic partial melting of an upper mantle source. Multiple injections of magmas derived from a PGE-rich source undergoing dynamic partial melting would have permitted enrichment of the PGE in sulfur-undersaturated residual liquids that remained in the Stillwater magma chamber after formation of the Ultramafic series. Fractional crystallization of olivine and orthopyroxene would have supplemented this enrichment in the PGE. Perturbation of this tholeiitic trend of fractional crystallization observed in the Ultramafic series due to the introduction of a plagioclase-rich, sulfur-saturated magma may have produced the cyclic modal and cryptic layering in Troctolite–Anorthosite zone I (TAZ I) and would provide an explanation for the location of the PGE-rich sulfides of the J–M Reef with a laterally continuous troctolite layer in TAZ I.

OCCURRENCE AND SIGNIFICANCE OF Co–PENTLANDITE IN THE UPPER ZONE OF THE WESTERN BUSHVELD

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Differentiation in magmatic bodies has a significant influence on bulk sulfide chemistry, which in turn is reflected 1) in different sulfide assemblages at different levels of the intrusive body, and 2) in the continuous compositional changes in individual sulfide minerals. In the upper zone of the (western) Bushveld Complex, olivine fractionation throughout the larger part of the sequence led to a more rapid depletion in Ni compared to Co, thereby reducing the bulk Ni/Co ratio of the magma and in the separated sulfide liquid. This upward decrease in the Ni/Co ratio resulted in such an increase of the Co content of the sulfide phase that almost pure cobalt pentlandite, having more than 85 mole % of the Co end member, exsolved from pyrrhotite on cooling close to the roof of the intrusive body.

The paper will document the evolutionary trend of pentlandite compositions and textures within rocks that crystallized from highly fractionated liquids. Compositional variations of pentlandite are discussed in the light of available whole-rock geochemistry, the Ni and Co content of the associated pyrrhotite, and composition of the associated silicates. Available data will also be used to evaluate whether the topmost cumulates of the upper zone represent uninterrupted fractional crystallization of one homogeneous magma.

NODULAR AND ORBICULAR PERIDOTITES OF FINLAND

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Rare orbicular rock textures, previously discovered only in felsic and intermediate igneous rocks, have now been encountered in two ultramafic rocks in Finland. The peridotitic host-rock of the Kylmäkoski Ni–Cu deposit in southwestern Finland displays nodular and orbicular textures of olivine. The nodules exhibit external crystal-forms of olivine and range in diameter from 1 to 4 cm. The cores of the macrocrystals are composed of coarse-grained poikilitic orthopyroxene and small individual olivine grains of the same material as the matrix of the nodules. The orbicular variety of Kylmäkoski peridotite displays oval spheres of olivine with a radial or poikilitic core composed of pyroxene. The spheres attain 7 cm in diameter.

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The orbicular peridotite discovered as blocks in a glacial float at Pisamaniemi, Kangaslampi, is barren of sulfides. The orbicular texture with radial prisms of pyroxene in the core of the olivine spheres is well developed and more regular than the orbicular texture of the Kylmäkoski peridotite. The textures resemble those rarely observed in nodular chromitites of podiform chromite deposits elsewhere. The texture of orbicular and nodular olivine has been attributed to rapid crystallization from a supercooled magma.

THE GEOLOGY OF A 2.2-KM SECTION OF THE WINDIMURRA LAYERED GABBRO, YILGARN BLOCK, WESTERN AUSTRALIA

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The Windimurra Complex is a 2200-km^2 elliptical Archean (>2.67 Ga) gabbroic intrusive body with an estimated thickness of approximately 9 km, in the northern Yilgarn Block of Western Australia. The body crops out as isolated blocks, and a complete stratigraphy is poorly defined. The exposed rocks typically consist of anorthositic gabbros, apart from an exposure of ultramafic rocks in an upfaulted block in the southern part of the complex.

A 2.2-km section of stratigraphy at Windimurra Hills, toward the east part of the complex, is documented in detail. The important minerals are olivine (Fo_{67-56}), augite [100Mg/(Mg + Fe) 76-70 at. %], hypersthene [100Mg/(Mg + Fe) 70-65 at. %], plagioclase (An_{79-72}) and titaniferous magnetite; the rocks are predominantly multiphase cumulates that collectively exhibit a modal dominance of cumulus plagioclase (~ 76%).

The stratigraphy is lithologically complicated, but is generally characterized by rhythmically layered thick anorthositic and thinner mafic zones, which are distinguished primarily on the basis of cumulus mineralogy and order of crystallization. Two such orders are evident: plagioclase → olivine → hypersthene → augite and plagioclase → olivine → augite → hypersthene. Olivine reappears as a cumulus phase at irregular intervals through the sequence and commonly forms thin (1 - 5 m) irregular olivine-rich layers that locally are associated with pyroxene pegmatites and with anorthositic "mixed rock" lithologies. The first appearance of significant cumulus titaniferous magnetite, halfway through the sequence, provides a stratigraphic marker horizon.

Phase compositions show an irregular trend toward a small amount of iron enrichment over the entire section. No reversals in compositional trends have yet been unequivocally identified to coincide with either changes in order of crystallization or loci of possible influx of magma. These patterns of irregular limited compositional and lithological diversity over large thicknesses of stratigraphy are features of other intrusive complexes at a similar stage of evolution, for example the middle of the Banded series, Stillwater Complex, Montana.

CRUSTAL CONTAMINATION OF THE SUBLAYER, SUDBURY IGNEOUS COMPLEX, AND ITS RELEVANCE TO THE GENESIS OF Ni–Cu SULFIDES

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The Ni–Cu ores in the Sudbury district are exclusively associated with the Sublayer, which is considered to result from a separate series of intrusions along the outer margin of the Sudbury Igneous Complex. The Sublayer ranges in composition from gabbro-norite to quartz diorite.

Sublayer rocks are characterized by relatively high abundances of SiO_2 (> 55 wt. %), K_2O (> 1.5%) and incompatible elements, significant enrichment in the light rare-earth elements when compared to con-

*Speaker.

tinental tholeiites with a similar Mg number, ϵSr ranging from + 13.0 to + 100, and ϵNd from -5.7 to 8.0. All of these facts indicate significant contamination of Sublayer magmas by crustal components.

The South Range Sublayer is characterized by ϵSr values ranging from + 60 to + 100 and high abundances of incompatible elements, whereas the North Range Sublayer has ϵSr values ranging from + 13 to + 34 and lower abundances of incompatible elements. These data are consistent with the proposal that the North Range Sublayer assimilated material from the immediately underlying Levack Gneisses, which have values similar to those that characterize lower-crust granulites (ϵSr between + 1.54 and − 15.2), in addition to a component of average upper crust. On the basis of the present data, a model involving the introduction of successive waves of magma from below, which interacted with distinctly different local environments, has been proposed for the emplacement of the Sublayer. This model has important implications with respect to the origin and character of the associated Ni–Cu ore deposits.

WHERE IS THE BUSHVELD'S MISSING PLATINUM?

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The most important mineralized unit of the Bushveld Complex is the Critical zone, which contains chromitite layers and is capped by the Merensky Reef. These layers are variably enriched in precious metals and sulfides. Minor PGE mineralization also occurs in the Upper zone.

The layered rocks of the 9-km-thick Complex are the products of fractional crystallization of two end-member magmas and their mixtures. Chilled marginal rocks provide clues to the composition of the two parental magmas and their derivatives. The older U (ultramafic) series are olivine boninites [SiO_2 52-56%, MgO 12-16%, Cr > 1000 ppm, Rb ~ 30 ppm, $Ce_N/Yb_N = 10$, $(^{87}Sr/^{86}Sr)_{2050}$ (R_0) 0.703-0.705]. No quenched end-member *A* magma is found, but its composition is deduced from the $U+A$ marginal rocks of the Upper Critical zone. The *A* (anorthositic) magma was tholeiitic, with Cr ~ 200 ppm, $Ce_N/Yb_N \sim 3$, Rb 3-4 ppm and $R_0 \sim 0.709$. Addition of *A* magma during the formation of the Critical zone and at the Merensky Reef can be monitored by the upward variation in R_0 of the layered cumulates.

The *U* magma was the PGE carrier. The *A* magma was barren of the PGE because: 1) sulfide-bearing Main zone (*A*) gabbros contain negligible concentrations of the PGE, and 2) quenched pyroxenitic ($U >> A$) marginal rocks low in the intrusive complex have similar precious-metal contents to chilled gabbroic ($U + A$) mixtures at the level of the UG-2 and Merensky Reef. Peridotite sills that sampled magmas at the crystallizing interface at various levels below the Merensky Reef show local upward increases in PGE_{liquid}, consistent with increases in the PGE tenor of mineralized layers.

The precious-metal budget of the Complex is unbalanced. Even though lower and Critical-zone cumulates are barren of PGE, the amount of the PGE contained in chromitite layers and the Merensky Reef is unsufficient in the light of high PGE contents in marginal rocks and sills.

The high R_0 of the Main zone (0.709) is achieved in a 300-m interval above the Merensky Reef. Within 10 m, at the "pyroxenite marker", 3 km higher in the Main zone, R_0 reverts to 0.707, similar to Merensky Reef values. The Main zone is interpreted as a "frozen" crystallized layer of *A* liquid, which was intruded close to the base of the magma chamber. At the base of the layer, rapid cooling of trapped, PGE-enriched $U + A$ precipitated the Merensky Reef, the PGE and sulfides. The $U + A$ magma column, enriched in precious metals, was elevated by the new magma, eventually to crystallize as subzone C of the Main zone and the magnetite-bearing Upper zone.

Where are the precious metals that were in the $U + A$ magma above the Merensky Reef? Minor PGE mineralization occurs beneath the main magnetite layer, and gold deposits occur locally along the roof contact of the Upper zone. Sulfide-mineralized magnetite gabbros can contain PGE. It appears that PGE mineralization in the Critical zone is associated primarily with chromitite layers, which originated by mixing between *U* or $U + A$ magmas and fresh *A* liquid. Isotopic and compositional discontinuities in the Upper zone that would reflect addition and mixing of different magmas might point to likely sites for undiscovered PGE mineralization.

PRECIOUS METALS ASSOCIATED WITH SULFIDE MINERALIZATION IN THE ELY–HOYT LAKES DISTRICT, DULUTH COMPLEX, MINNESOTA

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Sulfide-bearing samples from the Ely–Hoyt Lakes District of the Duluth Complex, Minnesota, were examined and placed into three major groups (cloud, basal, and hornfels) on the basis of their stratigraphic position and mineralogy. The basal group was subdivided into disseminated, massive, and epigenetic (veins within the footwall) types. The assemblages of low-temperature minerals found in samples within each group were used to infer the probable high-temperature solid-solution types originally present. Thirty-one sulfide separates representative of the groups were analyzed for their precious- and base-metal contents. The mineralogical and chemical data are shown in the table below.

Each zone, although it exhibits a range in composition, can be characterized by the relative abundances of the metals and the high-temperature solid-solution types. The cloud zone is characterized by abundant precious metals and moderate Cu; the hornfels zone by high Fe, moderate Ag, low Cu, Ni, and Pd. In the basal zone, the epigenetic veins, relative to the massive and disseminated types, exhibit enrichment of Cu, Pd and Ag accompanied by a depletion in Fe and Ni. Furthermore, the epigenetic veins in the footwall become more Cu-enriched with depth. Fractionation within the sulfide liquid probably caused the Cu enrichment and have provided a mechanism for the concentration of precious metals in the epigenetic veins.

Group	No.	SS Type	Fe,at.%	Cu,at.%	Ni,at.%	Pd,ppm	Ag,ppm
Cloud	7	iss ± mss	52-84	9-38	3-16	<0.5-28	57-267
Hornfels	2	mss	94-98	1-4	0.7-2	<0.5-3	44-140
Basal-m	6	mss	63-94	1-20	3-19	<0.5-4	42-115
Basal-d	11	mss ± iss	45-92	6-54	1-17	<0.5-7	47-147
Basal-e	5	iss ± bnss	30-57	43-69	0.3-3	0.7-5.5	44-187

THE BEHAVIOR OF THALLIUM AND ALKALI METALS IN THE NICKEL-SULFIDE-BEARING ULTRAMAFIC ROCKS AT KAMBALDA (WESTERN AUSTRALIA) AND VAMMALA (FINLAND)

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In crystallizing ultramafic magmas, thallium may exhibit both chalcophile and lithophile behavior, whereas the alkali metals potassium and rubidium behave only as lithophile elements. Nickel sulfide segregation from a crystallizing ultramafic magma to form an orebody seems to require that such separation should occur early in the crystallizing event. It has thus been proposed (McGoldrick *et al.* 1979) that depletion of thallium should occur relative to alkali metals in a magma that has segregated a sulfide melt, as thallium should be scavenged by the sulfide melt.

The relations between thallium and alkali metal chemistry in the mineralized and unmineralized parts of the Kambalda and Vammala ultramafic complexes have been studied. By using simple logarithmic XY plots and nonparametric statistical techniques, relations between thallium, potassium, rubidium and

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sulfur concentrations and geological data have been detected that indicate thallium geochemistry to be a powerful tool in the elucidation of crystallization history and the processes of sulfide saturation and segregation. Rock units that host ore, or are inferred to contain exsolved sulfides, do not show the same proportional increase in thallium content with differentiation as is exhibited by the alkali metals. In barren units, proportional increases of thallium and alkali metals are indeed identified.

The distinction between mineralized and unmineralized units suggests that the bulk of the sulfides separated from the host unit *in situ*; they were not transported directly from the mantle and did not separate from the larger body of magma now represented by the entire ultramafic sequence.

REFERENCES

McGoldrick, R.J., Keays, R.R. & Scott, B.B. (1979): Thallium: a sensitive indicator of rock/seawater interaction and sulfur saturation of silicate melts. *Geochim. Cosmochim. Acta* **43**, 1303-1311.