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Open-File Report 2012–1010

U.S. Department of the Interior
U.S. Geological Survey

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By Michael L. Zientek

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U.S. Geological Survey, Reston, Virginia 2012

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Suggested citation:
Zientek, M.L., 2012, Magmatic ore deposits in layered intrusions—Descriptive model for reef-type PGE and contact-type Cu-Ni-PGE deposits: U.S. Geological Survey Open-File Report 2012–1010, 48 p.

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Concise Description

Layered, ultramafic to mafic intrusions are uncommon in the geologic record, but host magmatic ore deposits containing most of the world's economic concentrations of platinum-group elements (PGE) (figs. 1 and 2). These deposits are mined primarily for their platinum, palladium, and rhodium contents (table 1). Magmatic ore deposits are derived from accumulations of crystals of metallic oxides, or immiscible sulfide, or oxide liquids that formed during the cooling and crystallization of magma, typically with mafic to ultramafic compositions.

"PGE reefs" are stratabound PGE-enriched lode mineralization in mafic to ultramafic layered intrusions. The term "reef" is derived from Australian and South African literature for this style of mineralization and used to refer to (1) the rock layer that is mineralized and has distinctive texture or mineralogy (Naldrett, 2004), or (2) the PGE-enriched sulfide mineralization that occurs within the rock layer. For example, Viljoen (1999) broadly defined the Merensky Reef as "a mineralized zone within or closely associated with an unconformity surface in the ultramafic cumulate at the base of the Merensky Cyclic Unit." In this report, we will use the term PGE reef to refer to the PGE-enriched mineralization, not the host rock layer. Within a layered igneous intrusion, reef-type mineralization is laterally persistent along strike, extending for the length of the intrusion, typically tens to hundreds of kilometers. However, the mineralized interval is thin, generally centimeters to meters thick, relative to the stratigraphic thickness of layers in an intrusion that vary from hundreds to thousands of meters.

PGE-enriched sulfide mineralization is also found near the contacts or margins of layered mafic to ultramafic intrusions (Iljina and Lee, 2005). This contact-type mineralization consists of disseminated to massive concentrations of iron-copper-nickel-PGE-enriched sulfide mineral concentrations in zones that can be tens to hundreds of meters thick. The modes and textures of the igneous rocks hosting the mineralization vary irregularly on the scale of centimeters to meters; autoliths and xenoliths are common. Mineralization occurs in the igneous intrusion and in the surrounding country rocks. Mineralization can be preferentially localized along contact with country rocks that are enriched in sulfur-, iron-, or CO_2-bearing lithologies.

Reef-type and contact-type deposits, in particular those in the Bushveld Complex, South Africa, are the world's primary source of platinum and rhodium (tables 2 and 3; fig. 2). Reef-type PGE deposits are mined only in the Bushveld Complex (Merensky Reef and UG2), the Stillwater Complex (J-M Reef), and the Great Dyke (Main Sulphide Layer). PGE-enriched contact-type deposits are only mined in the Bushveld Complex. The other deposits in tables 2 and 3 are undeveloped; some are still under exploration.

Commodities (By-Products)

Reef-type PGE deposits: primarily platinum, palladium, and rhodium; copper, nickel, ruthenium, iridium, osmium, and gold will be recovered as by-products.

Contact-type Cu-Ni-PGE deposits: polymetallic, with variable proportions of copper, nickel, and platinum-group elements, and by-product gold.

Associated Deposit Types

Associated deposit types include stratiform chromitite (Schulte and others, 2010), stratiform titanium-vanadium (Force, 1991), and magmatic sulfide-rich nickel-copper deposits related to picrite and (or) tholeiitic basalt dike-sill complexes (Schulz and others, 2010).

Ore System Components

The exsolution of immiscible sulfide liquid from mafic silicate magma is the fundamental ore-forming process in the genesis of PGE mineralization in layered igneous intrusions. Once droplets of immiscible sulfide liquid form in silicate magma, they act as "collectors" for copper, nickel, and PGE because these elements will be preferentially concentrated into the sulfide liquid relative to the silicate liquid.

The solubility of sulfur in mafic magmas is affected by changes in the bulk composition of the magma, the fugacity of sulfur and oxygen, temperature, and pressure. Once magma becomes saturated in sulfur, it can exsolve an immiscible sulfide liquid. Processes that change the solubility of sulfur and may cause an exsolution event include fractional crystallization of the silicate magma, mixing of magmas, assimilation of sulfur from sources external to the magma, and modification of magma composition by bulk contamination, for example, changing the silica content.

Layered igneous intrusions hosting reef-type and contact-type deposits are found in geologic settings characterized by the rapid emplacement of voluminous amounts of mafic and ultramafic magma into continental crust. Depleted, lithospheric mantle stabilized beneath cratons can generate PGE-rich “second-stage” melts that may be important in generating these types of deposits (Mungall, 2005; Green and Peck, 2005; Naldrett, 2010a, b).

Regional Environment

With one exception, ultramafic to mafic layered intrusions that host reef-type PGE and contact-type Cu-Ni-PGE deposits are associated with large igneous province (LIP) magmatism (fig. 3, table 4). On continents, LIP-associated rocks include continental flood basalts, aerially extensive mafic dike swarms, sill provinces, and large layered ultramafic to mafic intrusions (Coffin and Eldholm, 1994). Bryan and Ernst (2008) proposed that “Large Igneous Provinces are magmatic provinces with areal extents $>1 \times 10^5$ km^2, igneous volumes $>1 \times 10^5$ km^3 and maximum lifespans of <50 Myr that have intraplate tectonic settings or geochemical affinities, and are characterized by igneous pulse(s) of short duration (<1–5 Myr), during which a large proportion (>75 percent) of the total igneous volume has been emplaced. They are dominantly mafic, but also can have significant ultramafic and silicic components, and some are dominated by silicic magmatism."

Unlike the vast majority of igneous rocks that are associated with plate tectonic processes at convergent or divergent tectonic plate margins, LIP-related igneous rocks usually occur in an intraplate tectonic setting. Some LIPs are linked to hotspot tracks; for example, the North Atlantic Igneous

Province has been linked to the Iceland hotspot (Storey and others, 2007). Regional uplift and doming may be another characteristic of these provinces.

Within a LIP, layered igneous intrusions hosting reef-type PGE and contact-type Cu-Ni-PGE deposits range in size from plutons covering about 100 km^2 to lopoliths that exceed 50,000 km^2 in extent. For example, the Skaergaard Intrusion in Greenland that hosts the Platinova Reef is an irregular, 11 × 8 km, oval-shaped body (Nielson, 2004). The Bushveld Complex, South Africa, is the world's largest layered mafic intrusion, extending more than 350 km in both north-south and east-west directions (Webb and others, 2004). These intrusions display igneous layering defined by variations in modal proportions of minerals, rock textures, grain size, and mineral compositions. Individual layers range from millimeters to tens of meters in thickness and may extend for hundreds of kilometers along strike. The thickness of the layered intrusions ranges from hundreds of meters to as much as 10 km.

Layered ultramafic and mafic intrusions are studied using stratigraphic mapping techniques. Sections of layered igneous rock are measured and the thickness of layers, along with their composition and textures, are described. Layers are grouped into stratigraphic units that are distinguished on geologic maps. Stratigraphic sections and the resulting maps are used to describe the distribution and geometry of the layered igneous rocks and to understand the crystallization history of the intrusion.

Fractionation patterns in PGE-bearing layered igneous intrusions indicate some were emplaced and solidified as closed systems, whereas others show evidence for repeated injections of magma. An example of a closed system would be the Skaergaard Intrusion, Greenland (McBirney, 1995). The intrusion crystallized inward from the bottom, the sides, and the top, with the last fractionated magmas solidifying in a "sandwich" horizon. Changes in mineral composition with stratigraphic position show trends and patterns consistent with the expected crystallization pattern of a mafic magma. Most of the large layered igneous intrusions, such as the Bushveld Complex, the Stillwater Complex, and the Great Dyke show evidence for open-system behavior. The stratigraphic record for these intrusions show thick intervals in which mineral compositions do not change, abrupt changes in mineral crystallization orders, and discontinuities in fractionation trends that are not consistent with the expected crystallization of a mafic magma.

Age Range

These deposit types occur throughout Earth's history, but seventy-five percent of known PGE resources occur in three Paleoproterozoic and Neoarchean intrusions: the Bushveld, Great Dyke, and Stillwater (Naldrett, 2010b). Absolute age information for many of the intrusions hosting reef-type and contact-type deposits is summarized in table 4. With the exception of two Tertiary intrusions, La Perouse in Alaska and Skaergaard in Greenland, all intrusions are Mesoproterozoic and older.

Deposit Features

Reef-Type PGE

Reef-type PGE deposits consist of stratabound disseminated iron-, copper-, nickel-, and PGE-bearing sulfide minerals that are associated with one or more layers within a layered igneous intrusion (table 3). The host rocks for the disseminated sulfide minerals include silicate cumulates such as (1) plagioclase-olivine cumulates that host the J-M Reef in the Stillwater Complex, (2) orthopyroxene cumulates that are associated with the Merensky Reef in the Bushveld Complex, and (3) pyroxene cumulates that host the Main Sulphide Zone in the Great Dyke, as well as oxide cumulates such as

(4) the UG2 chromitite in the Bushveld Complex, and (5) the iron-titanium oxide layers in the Stella Intrusion in South Africa (fig. 1).

The PGE reefs are typically in stratigraphic intervals that mark a major lithologic and petrologic change in the layered igneous intrusion (fig. 4). The Main Sulphide Layer of the Great Dyke in Zimbabwe and the Ferguson Reef of the Munni Muni Complex in Western Australia are found near the contact between the lower parts of the section composed entirely of ultramafic cumulates and the upper parts dominated by mafic cumulates (fig. 4).

The change may also correspond to the appearance or disappearance of a cumulus mineral, particularly where high-magnesium phases reappear in the section above where they had initially stopped crystallizing. The appearance and disappearance of minerals in the stratigraphic section may reflect the normal evolution of silicate magma. For example, cumulus olivine and chromite crystallize early in the sequence, whereas cumulus iron-titanium oxide minerals and apatite characteristically appear in the upper parts of a section of layered igneous rocks, consistent with crystallization of an evolved magma. However, for the J-M Reef of the Stillwater Complex, Montana, reef-type mineralization is associated with the reappearance of magnesian olivine in the stratigraphic section and a change in the crystallization order of silicate and oxide minerals, as interpreted from rock textures.

The J-M Reef (Stillwater), Merensky Reef and UG2 chromitite (Bushveld), Siika-Kämä Reef (Narkaus Intrusion, Finland), and Sompujärvi Reef (Penikat Intrusion, Finland), are found at the base of cyclic units. Cyclic units are sequences of related igneous layers that repeat many times in the stratigraphic section (Jackson, 1970). The lowest rocks in a sequence may be ultramafic cumulates, which in turn grade upwards into gabbroic and anorthositic cumulates. The anorthositic cumulates at the top of one cyclic unit will be overlain by ultramafic rocks of the next cycle.

Petrologic studies of the PGE reefs show that the stratigraphic interval hosting the sulfide mineralization may be characterized by stratigraphic discontinuities in silicate mineral fractionation trends and abrupt changes in the initial ratios of Nd and Sr isotopes (fig. 5) in the igneous rocks. The best example of isotopic discontinuities associated with mineralization is the Merensky Reef in the Bushveld Complex (Kruger, 1994; Teigler, 1990).

The interval hosting PGE reefs may also mark the position where the magmas achieved sulfur saturation in the stratigraphic column. This is indicated by the presence of disseminated sulfide minerals or changes in metal ratios, such as Pd/S (Barnes, 1993; Miller and others, 2002; Maier and others, 1996, 2003; Maier, 2005; Maier and Barnes, 2010). Sulfur saturation may be associated with iron-rich cumulate layers, such as chromitites and iron- and titanium-rich magnetite seams, or with iron-rich silicate rocks resulting from the end-stages of fractional crystallization (fig. 6).

Detailed mapping and stratigraphic studies of the igneous layers hosting reef-style mineralization associated with the Merensky Reef (Smith and Basson, 2006), UG2 chromitite in the Bushveld Complex (van der Merwe and Cawthorn, 2005), and with the J-M Reef (Barnes and Naldrett, 1986) in the Stillwater Complex have documented that the younger, overlying stratum does not "conform" to the dip and strike of the older underlying layered igneous rocks (fig. 7). Following South African terminology, these igneous unconformities are called “potholes.”

Not every stratabound occurrence of magmatic sulfide minerals in layered igneous rocks contains elevated PGE concentrations. Examples in the Bushveld Complex include the barren stratabound sulfide concentrations in the Pyroxenite Marker Unit and the main magnetite layer in the Bushveld Complex (Harney and others, 1990; Maier and others, 2001; Barnes and others, 2004; Maier and Barnes, 2010).

Contact-Type Deposits

Copper-nickel-PGE-gold contact-type deposits (table 4) consist of disseminated, net-textured, and massive copper-nickel-PGE-enriched sulfide minerals found near the lower contact or margin of mafic to ultramafic layered intrusions. The host rocks for the disseminated sulfide minerals include both the igneous rocks and contact metamorphosed country rocks.

The sulfide mineralization is found adjacent to or along strike with country rocks that are enriched in sulfur-bearing, iron-bearing, and (or) carbonate minerals. The mineralization can be laterally persistent, commonly extending the strike length of the layered igneous intrusion. However, the mineralized interval is generally tens to hundreds of meters in thickness. The proportion of sulfide minerals varies along strike; using economic cut-offs, areas with higher proportions of sulfide minerals and metals are defined as deposits along the contact zone.

Sulfide abundance is typically about 3 to 5 volume percent, but matrix and massive sulfide ores may be present. Erratic variation in the distribution of sulfide minerals is typical, although, the concentration of sulfide minerals within the intrusion generally increases towards its margins and in the adjacent country rocks.

Host Rocks

Reef-Type Deposits

The igneous intrusions hosting reef-type PGE deposits almost entirely comprise layered cumulates composed of olivine, orthopyroxene, clinopyroxene, plagioclase, chromite, and Fe-Ti oxide minerals. Igneous rocks can be classified using modal mineralogy (Le Maitre and others, 2002) and color index (leucocratic vs. melanocratic). However, for layered igneous intrusions, cumulus terminology based on modal mineralogy, texture, and composition is also used.

Cumulates are igneous rocks characterized by distinctive textural and compositional features (Jackson, 1967; Irvine, 1982). These rocks consist of high-temperature minerals that crystallize from mafic to ultramafic silicate melts, but in proportions that are not appropriate for the bulk composition of naturally occurring mafic magma. In addition, cumulates are depleted in minerals that crystallize late from magmas and elements that behave incompatibly during crystallization.

Textures of cumulates are characterized by fabrics that consist of a "framework" of anhedral to euhedral crystals (cumulus crystals) "cemented" by minerals interstitial to the cumulus grains (Wager and others, 1960). Postcumulus interstitial material may form crystallographically continuous grains that surround and include cumulus crystals, fill intergranular interstices, or form overgrowths on existing cumulus crystals.

The textural emphasis of cumulus nomenclature documents the sequence of mineral crystallization, which in turn provides a general indication of primary magma composition. For example, the sequence plagioclase-clinopyroxene-olivine or plagioclase-olivine-clinopyroxene is consistent with experimental results for the crystallization sequence of tholeiitic magma. The sequence olivine-clinopyroxene would be consistent with magnesium-rich magmas, such as komatiite. The sequence olivine-orthopyroxene-plagioclase appears to represent the crystallization order of siliceous high-magnesium basaltic magma.

Contact-Type Deposits

The igneous host rocks of contact-type PGE deposits include cumulate and noncumulus rocks. If the cumulates near the contact are gabbroic, the igneous rocks in the contact zone will be gabbroic. If the cumulates near the contact are ultramafic, then the contact zone igneous rocks will be dominated by pyroxenites and norites. Some lithologies are cumulates, but other mineralized mafic and ultramafic igneous rocks are texturally and lithologically heterogeneous, exhibiting changes in texture and mineral proportions on a variety of scales from centimeters to meters. Textures indicative of chilling or unidirectional growth may be present. In literature these rocks are described as vari-textured, heterogeneous texture, or taxitic. Mineral fractionation patterns of ferromagnesian minerals commonly show magnesium enrichment trends upsection, away from the intrusive contact. Inclusions of autholiths and xenoliths are common; they are surrounded by igneous rocks that have textural, mineralogical, and isotopic features suggestive of reaction (Iljina and Lee, 2005). Sulfur isotopic compositions of the sulfide deposits commonly indicate the presence of crustal sulfur. The country rocks are contact metamorphosed and may show evidence for partial melting near the intrusive contact (Johnson and others, 2003; Thomson, 2008).

PGE, Sulfides, and Sulfide Liquid Immiscibility

The PGE-, copper-, and nickel-bearing sulfide minerals define the ore phases in the igneous rocks. Primary sulfide phases include pyrrhotite, pentlandite, chalcopyrite, and bornite. The sulfide minerals are complexly intergrown and form fine- to coarse-grained aggregates that are molded around and are interstitial to the cumulus or earlier formed silicate minerals, or occur as fine-grained, rounded inclusions in silicate or oxide minerals. The PGE occur in solid solution in sulfide minerals and also as discrete platinum-group minerals (PGM). The PGM can be included in sulfide minerals or chromite, or they can be concentrated along grain boundaries between sulfide minerals or between sulfide and silicate minerals.

Textural and experimental evidence indicate that the PGE-enriched sulfide mineralization formed as an immiscible sulfide liquid that exsolved from mafic to ultramafic magma (Barnes and others, 2008; Holwell and McDonald, 2010; Naldrett, 2010a). When not modified by weathering or alteration, the textures between silicate and sulfide minerals record the distribution and abundance of the sulfide liquids and the interaction between solid silicate minerals and sulfide liquid.

Solubility of sulfur in magma is a function of magma composition and oxygen fugacity; in systems lacking a free sulfide phase, the amount of sulfur dissolved in the silicate melt, ${S_{sil}}^{-2}$, follows this mass action equation (Mungal, 2005):

$$ {S_{sil}}^{-2} + {}^{1}\!/_{2}\, O_2 = {O_{sil}}^{-2} + {}^{1}\!/_{2}\, S_2 \; K_{10} $$

Assuming that the concentration of O^{-2} does not change appreciably in the silicate melt, the concentration of S^{-2} can be related to a constant similar to an equilibrium constant:

$$ C_s \equiv \; X_{S^{-2}} \times \frac{fO_2^{1/2}}{fS_2^{1/2}} = \frac{K_{10}}{X_{O^{-2}}} = constant, $$

where C_s is the sulfide capacity and is a constant for a given melt composition at a given temperature. C_s is a strong function of the silicate melt, increasing with increasing temperature, X_{FeO}, X_{TiO_2} and decreases with increasing pressure, X_{SiO_2}, and $X_{Al_2O_3}$ (Mungal, 2005).

Silicate melts become FeS undersaturated as they rise into the crust and fractional crystallization takes place, although assimilation of crustal rocks promotes slight oversaturation. Assimilation of sulfidic sedimentary rocks promotes extreme oversaturation. Magma composition changes that will promote sulfide liquid exsolution can be the result of assimilating sulfur, bulk assimilation of country rocks, mixing magmas, or fractional crystallization (Ripley, 1999). Venting the magma chamber can change pressure, which can also promote sulfide liquid immiscibility.

Processes That Determine Composition of Ores

The metal content of immiscible sulfide liquids is a function of the (1) amount of metal in the silicate magma; (2) relative affinity for metals to occur in the sulfide or silicate liquid, expressed as a partition coefficient; and (3) relative amounts of the two liquids, expressed as a mass ratio of silicate to sulfide liquid (Campbell and Naldrett, 1979; Barnes and Maier, 1999),

$$C_{sul} = C_0 D^{sul/sil} \frac{R+1}{R+D^{sul/sil}}$$

where C_{sul} is the concentration of metal in the sulfide liquid, C_0 is the initial concentration of the metal in the silicate liquid, R is the mass ratio of silicate to sulfide liquid, and $D^{sul/sil}$ is the partition coefficient of the metal between sulfide and silicate liquid. For example, the initial amount of nickel and copper in the magma will determine the nickel and copper concentrations in the corresponding sulfide liquids and the resulting ores. Komatiitic magmas, with high nickel and low copper concentrations, will give rise to nickel-rich magmatic ores. Tholeiitic magmas, with lower nickel and higher copper, will produce ores with more copper than nickel. The PGE, Cu, and Ni are chalcophile, and, therefore, they are highly compatible with sulfide melt with respect to silicate melt. Once an immiscible sulfide liquid forms in a silicate melt, chalcophile elements concentrate into the sulfide liquid in proportion to their effective partition coefficients. Estimates of the partition coefficients for Ni and Cu between sulfide and silicate liquids are in the hundreds; for the PGE, they range from thousands to tens of thousands (Mungal, 2005; Naldrett, 2010a). The high coefficients, particularly for the PGE, imply that concentration of metals into the sulfide liquid can cause significant drops of the metal in the silicate magma. The distribution equation was modified by Campbell and Naldrett (1979) to allow for differing proportions of magma and sulfide liquid. Low values of the mass ratio of silicate to sulfide liquid are associated with deposits with higher proportions of sulfide minerals and lower concentrations of PGE, which are the contact-type deposits. High values of the mass ratio are associated with deposits with lower proportions of sulfide minerals and high PGE grades, which are the reef-type deposits (Mungall, 2005).

Large mass ratios of silicate to sulfide liquid can be achieved by mixing magmas, migrating interstitial melts (and “fluids”) upward through crystal mush, and streaming magma over sulfide liquids in a channelized lava flow, a sill, or feeder dike (Mathez, 1999; Barnes and Maier, 1999; Naldrett, 2010a).

In addition to copper, nickel, PGE, and gold, magmatic ores contain minor amounts of silver, and semi-metals and metalloids such as arsenic, antimony, bismuth, and tellurium.

Mineralogy and Textures

The textures and mineralogy of the ores record a prolonged and complex process of solid state transformation and recrystallization after solidification of the sulfide liquid at temperatures in excess of 900°C (Barnes and others, 2008; Holwell and McDonald, 2010; fig. 8). Depending on the initial composition of the immiscible liquid, the early formed solid products will consist of some mixture of the minerals monosulfide solid solution (MSS), intermediate solid solution (ISS), and bornite solid solution (BNSS). High-temperature monosulfide solid solution exsolves, forming mixtures of pyrrhotite and pentlandite. Breakdown products of intermediate solid solution include copper- and iron-bearing sulfide minerals such as chalcopyrite.

At high temperature (about 1,000°C), osmium, iridium, and ruthenium will partition into MSS from the immiscible sulfide liquid. Platinum, palladium, and gold behave as incompatible elements with respect to MSS and are concentrated in residual sulfide liquids. These elements are associated with the final crystallization products of the immiscible sulfide liquid. Upon cooling, some of the PGE that are held in sulfide crystal structure are expelled, forming discrete minerals including sulfides, arsenides, tellurides, antimonides, and alloys. Platinum and gold occur primarily in discrete small PGM, ranging in size from tenths to tens of microns. Significant quantities of palladium can be held in solid solution in pentlandite.

Subsolidus equilibration of sulfide minerals with the enclosing silicate-rich or oxide-rich rock may modify the bulk composition of the sulfide mineral assemblage (Naldrett and von Gruenewaldt, 1989). The greatest change would be expected for sulfide inclusion in silicate or oxide minerals where the sulfide grain size is small, generally tens of microns, and the abundance is low.

Ore textures can be substantially modified by alteration and weathering. Hydrothermal alteration can replace sulfide minerals with actinolite, tremolite, epidote, or calcite (Li and others, 2004). In the UG2, platinum minerals remain within the replacement aureoles after silicate and carbonate minerals replaced the magmatic sulfide minerals. During serpentinization, magnetite can replace sulfide minerals.

Minerals formed during alteration and weathering can include violarite, bornite, mackinawite, cubanite, pyrite, marcasite, troilite, vaesite, smythite, polydymite, millerite, hematite, and magnetite. In supergene environments, chalcocite, malachite, native copper, cuprite, nickel-iron carbonates, nickel and nickel-iron hydroxycarbonates, and nickel-silicates may form. Gossans may form above sulfide-rich rocks.

Variation in PGE and Other Metal Grades

The distribution and modal abundance is a primary control on the concentrations of copper, platinum, palladium, and gold in reef-type PGE and contact-type deposits. However, the distribution of sulfide minerals is not uniform within a mineralized interval. In addition, the PGE are variably enriched in the sulfide minerals. Stated another way, not every part of a mineralized layer will contain economic quantities of sulfide minerals and the area of greatest abundance of sulfide minerals may not show the highest concentrations of PGE.

Reef-Type PGE—Relation of Thickness of Layer and Grade

The PGE-rich layer in the Great Dyke, the Main Sulphide Zone, is higher grade where thinner and lower grade where thicker (Wilson and Brown, 2005). The thinner, higher grade parts of this reef are located along the margins of the intrusion. The mineralized layer becomes thicker, but lower grade towards the axis of the dike. Facies of the Merensky Reef and UG2 show similar patterns (figs. 9 and 10); in the Amandebult section, the vertical value distribution of the Merensky Reef decreases as the thickness of the reef increases (Viljoen and others, 1986). However, drill data for the Ferguson Reef in the Munni Munni intrusion and the Stillwater Complex do not show any relation between the thickness of the mineralized interval and its grade (fig. 10).

Reef-Type PGE—Concentration Profiles

The sulfide mineralization of PGE reefs is stratabound, associated with, but not restricted to a single igneous layer. Vertical profiles through rock layers that host PGE reefs show that the distribution of sulfide minerals and their metal concentration is not uniform. The modal abundance of sulfide minerals usually does not vary systematically, instead forming patterns of peaks and troughs that may or may not correspond to layering features. For the Merensky Reef, peaks in copper, PGE, and gold correspond to peaks in the concentration of sulfur in the rock (Wilson and Chunnett, 2006). For the J-M Reef, rocks with the highest modal proportion of sulfide minerals also have the highest PGE concentrations (Zientek and others, 1990; fig. 11). However, several reefs show concentration profiles where the peak concentrations of platinum and palladium are offset stratigraphically below the peak concentrations of sulfur and copper, and thus sulfide mineral abundance. Examples include the Ferguson Reef of the Munni Munni Intrusion (Barnes and others, 1990), the Main Sulphide Layer of the Great Dyke (Naldrett and Wilson, 1990; fig. 12), and the Platinova Reef in the Skaergaard Intrusion (Andersen and others, 1998). An extreme example is the mineralization in Rincon del Tigre in Bolivia where peak concentrations of platinum, palladium, and gold are tens of meters stratigraphically below the highest concentration of copper and sulfide minerals (Prendergast, 2000; fig. 6). For offset-type reefs, small quantities of sulfide minerals below the more voluminous concentrations have the highest PGE concentrations. Sulfide minerals higher in the section, although more abundant, have lower PGE concentrations.

Reef-Type PGE—Variation Along Strike

Sulfide minerals are not always concentrated uniformly in the plane of layering of reef-type deposits. The reef deposits are characterized by both near- and long-range variability in sulfide mineral abundance and PGE grade. The variation partly reflects difficulties in obtaining representative samples for analysis, but also includes actual differences in the abundance of sulfide minerals and their PGE enrichment along strike.

Resource estimates for reef-type deposits are determined by drilling and assaying drill core or cuttings. In practice, a large disparity in PGE grades may be found between adjacent samples due to the complex, erratic, and localized distribution of sulfide minerals and PGM. This “nugget effect” makes it difficult to estimate grade for reefs. The strategy for minimizing this problem is to increase the density of drilling and the use of replicate analysis of the samples. Replication strategies include analyzing different splits of the drill core, reanalyzing pulps, and using wedges to deflect the bit in a drill hole to obtain several closely spaced samples of a potentially mineralized interval.

After the “nugget effect” is minimized, drilling and mapping show variation in the abundance of sulfide minerals and their grade that can be measured on the scale of tens of meters. Early in the development of the Stillwater mine, about one-third of the definition drill holes on the J-M Reef, drilled on 15-m centers, did not encounter significant mineralized zones. By selectively mining approximately 30 to 40 percent of the volume of the reef, 80 percent of the contained metal was recovered (R.W. Vian, oral commun., 1989; see also Raedeke and Vian, 1986). Lateral variations in PGE grade are also characteristic of the Merensky Reef and the UG2 chromitite in the Bushveld Complex. Local variations, on the scale of an individual mine property, require closely spaced drilling to estimate resources and develop mine plans (Viljoen and Hieber, 1986; Gray and others, 2008; fig. 13).

Regional-scale variations in the overall grade of the mineralized interval are also evident when grades are mapped for mine properties. For the Bushveld Complex, there is significant variation in the grade in Merensky Reef and the UG2 along strike, although mines tend to have higher grades in the western part of the intrusion (figs. 14 and 15).

Contact-Type Deposits

The absolute PGE contents and relative proportions of PGE content to the base metals vary erratically in these deposits (Iljina and Lee, 2005). Sulfide mineral distribution is patchy, forming clouds of clot-like sulfide mineral aggregates interstitial to igneous silicate minerals. Mineralized units tens of meters thick can be correlated between drill holes. However, individual clouds or lenses of mineralization have limited continuity (usually less than the drill spacing). Along the contact of the intrusion, the sulfide minerals are concentrated into discrete areas or domains that can be delineated as separate deposits (Peterson and others, 2004). In individual drill holes, the highest PGE values can be found tens of meters above or below the contact of the intrusion; they are also variable along the strike (Iljina and Lee, 2005). The highest concentration of PGE is not necessarily associated with the highest concentration of sulfide minerals (Zientek, 1993; Iljina and Lee, 2005).

Geophysical Characteristics for Exploration

Geophysical methods map physical property contrasts, primarily sulfide minerals, and magnetite that may be associated with mineralization, but not PGE directly (Balch, 2005). Detailed aeromagnetic surveys are used to establish a geologic framework of an area (Campbell, 2006) and generally do not give direct indication of mineralized rock. High-resolution surveys can be used to map igneous layering and tectonic structures, particularly if the data are enhanced to distinguish subtle features. Gravity studies are used to determine the subsurface extent of rocks with variable density and are particularly well suited to map and model the extent and volume of mafic and ultramafic igneous rocks (Webb and others, 2004). However, gravity measurements are not used to directly locate mineralized rocks.

Electrical methods work best on rocks that are conductive. For contact-type deposits, airborne and ground electromagnetics and induced polarization surveys can be used to identify and delineate rocks that contain conductive and interconnected net-textured or massive sulfide ores. For reef-type ores, with low sulfide mineral contents, electrical responses are subtle (Balch, 2005).

Once a rock layer that contains reef-type mineralization has been identified, seismic studies can be used to map the subsurface extent of the rocks. Three-dimensional seismic surveys can identify faults, slumps, and potholes that affect the Merensky Reef (Davison and Chunnett, 1999; Chunnett and Rompel, 2004).

Geochemical Characteristics for Exploration

The best guide to ore is the presence of sulfide minerals and their iron-oxide replacement products. However, a practical and effective exploration approach is to look for anomalous concentrations of copper, platinum, and palladium in residual or transported material derived from a larger volume of rock. The Merensky Reef was discovered in 1924 as the result of panning in a dry river bed and finding platinum minerals in the concentrate (Cawthorn, 1999). The J-M Reef of the Stillwater Complex was discovered in 1974 by analyzing soil and talus fines for platinum and palladium (Conn, 1979; Zientek and others, 2005; fig. 16). Over 10,900 samples were collected and analyzed; more than 95 percent of them had less than 30 to 40 parts per billion (ppb) palladium and less than 40 to 50 ppb platinum. Most of the anomalous samples had 40 to 200 ppb palladium and 50 to 200 ppb platinum. Highly anomalous samples could have thousands of parts per billion platinum and palladium. Soil chemistry is also used to delineate mineralization in the Platreef (Frick, 1985). Regional glacial till geochemical surveys are being used to explore for contact-type mineralization in the Duluth Complex (Duluth Metals, 2011).

Assimilation of country rocks is proposed to be an important mechanism for initiating the exsolution of immiscible sulfide liquids in contact-type deposits. Sulfur isotopes, various radiogenic isotopes, and sulfur-selenium ratios are used to study assimilation processes in contact-type ores (Ripley, 1999; Iljina and Lee, 2005). Mantle-derived sulfur has $\delta^{34}S$ values near zero per mil. Contact-type mineralization may have $\delta^{34}S$ values intermediate between mantle values and values characteristic of sulfur in adjacent metasedimentary rocks. For example, in the Dunka Road contact-type deposit in the Duluth Complex, the $\delta^{34}S$ values of sulfides in the mineralized troctolites range from 0.2 to 15.8 per mil, with an average value near 7.5 per mil. Pyrrhotite in the underlying Virginia Formation hornfels and pyrite from unmetamorphosed Virginia Formation are characterized by a similar range in $\delta^{34}S$ values (Ripley, 1981). Sr-isotope and Nd-isotope studies of the Platreef in the Bushveld Complex are consistent with local contamination of an already contaminated magma (Pronost and others, 2008).

Deposit Size and Grade Characteristics

Reef-Type PGE Deposits

The average grades of PGE reefs that are being mined or actively explored, expressed as the sum of all PGE and gold, range from about 3 to 20 g/t (table 2; figs. 17 and 18). The thickness of the mineralized layers range from less than 1 m to about 25 m. Grades and thickness vary within a deposit along strike. The reef-type PGE deposits vary considerably in grades of platinum, palladium, rhodium, and gold.

Tonnages of PGE reefs are positively correlated with the size of the layered igneous intrusion (Green and Peck, 2005; Naldrett, 2010a). For example, the areal extent of the Bushveld Complex is about 60,000 km^2 and about 4.2 billion tons of ore have been identified for the Merensky Reef. The Stillwater Complex has an aerial extent of approximately 200 km^2; the total resource delineated for the J-M Reef is about 320 million tons.

Contact-Type Deposits

Contact-type mineralization is not uniformly concentrated in the igneous and country rocks near the margin of a layered intrusion. During exploration , economic cut offs are used to define the margins of deposits; low grade mineralization may occur outside the cut-off limit that defines deposits. The cut-off criteria used for resource estimation varies by deposit and includes grade, metal-equivalent values, gross metal value (GMV), net metal value (NMV), and metal density (table 5). In table 3, resources for sites within 1 km of each other, measured from the outer edge of the economic cut-off boundary, were grouped for reporting purposes.

Histograms, box plots, and normal quantile plots of contact-type deposits are shown in figures 19 and 20 and summary statistics are given in table 6. Missing data in table 3 are a result of nonreporting rather than absence of the commodity. The median value of ore for the 37 known contact-type deposits is 70 million tons, with median grades of 0.16 percent nickel, 0.25 percent copper, 0.245 g/t platinum, 0.62 g/t palladium, and 0.0846 g/t gold. The frequency distributions for tonnage and grade are positively skewed but can be normalized, using a log transformation, in order to use parametric statistical tests. Copper, nickel, platinum, and palladium frequency distributions for contact-type deposits are multi-modal as shown by multiple peaks on the histograms and changes in slope on the normal quantile plots. The populations appear to be related to deposits associated with an intrusion or intrusions derived from the same LIP event (figs. 20, 21, and 22). For example, analysis of variance shows that tonnage and the concentrations of copper, platinum, and palladium in deposits associated with the Bushveld, Keewenawan, and Baltica LIP events are characterized by statistically distinct distributions (figs. 20 and 21). Resource estimation using all 37 deposits as a universal grade and tonnage model is not appropriate. If enough data are available, grade and tonnage models should be developed for each LIP event for which there is data.

Acknowledgments

Doug Causey provided results of his compilation of mineral resource data for the Bushveld Complex. Reviews by Rich Goldfarb and Ryan Taylor substantially improved the manuscript. Ken Assmus, Heather Overstreet, and Kassandra Lindsey helped prepare illustrations for the report.

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Additional Reading

This a partial list of books, papers, and digital datasets that summarize magmatic ore deposits, reef-type, and contact-type deposits not cited in this report but that should be part of a reading list for understanding these deposit types.

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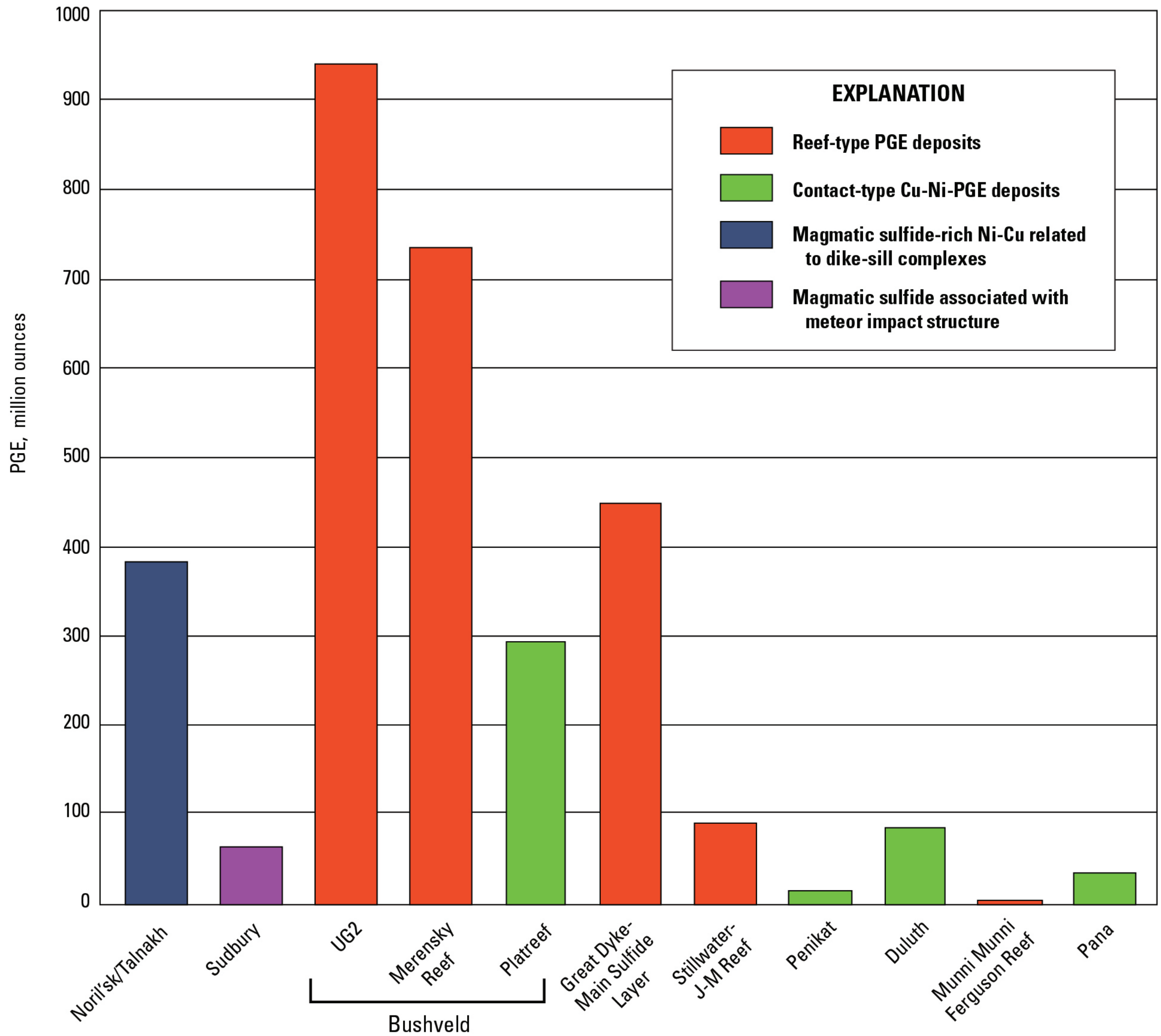

Figure 1. Histogram of the major world platinum-group elements (PGE) deposit resources. Reef-type deposits and contact-type deposits are shown in red and green, respectively. Data from Green and Peck (2005).

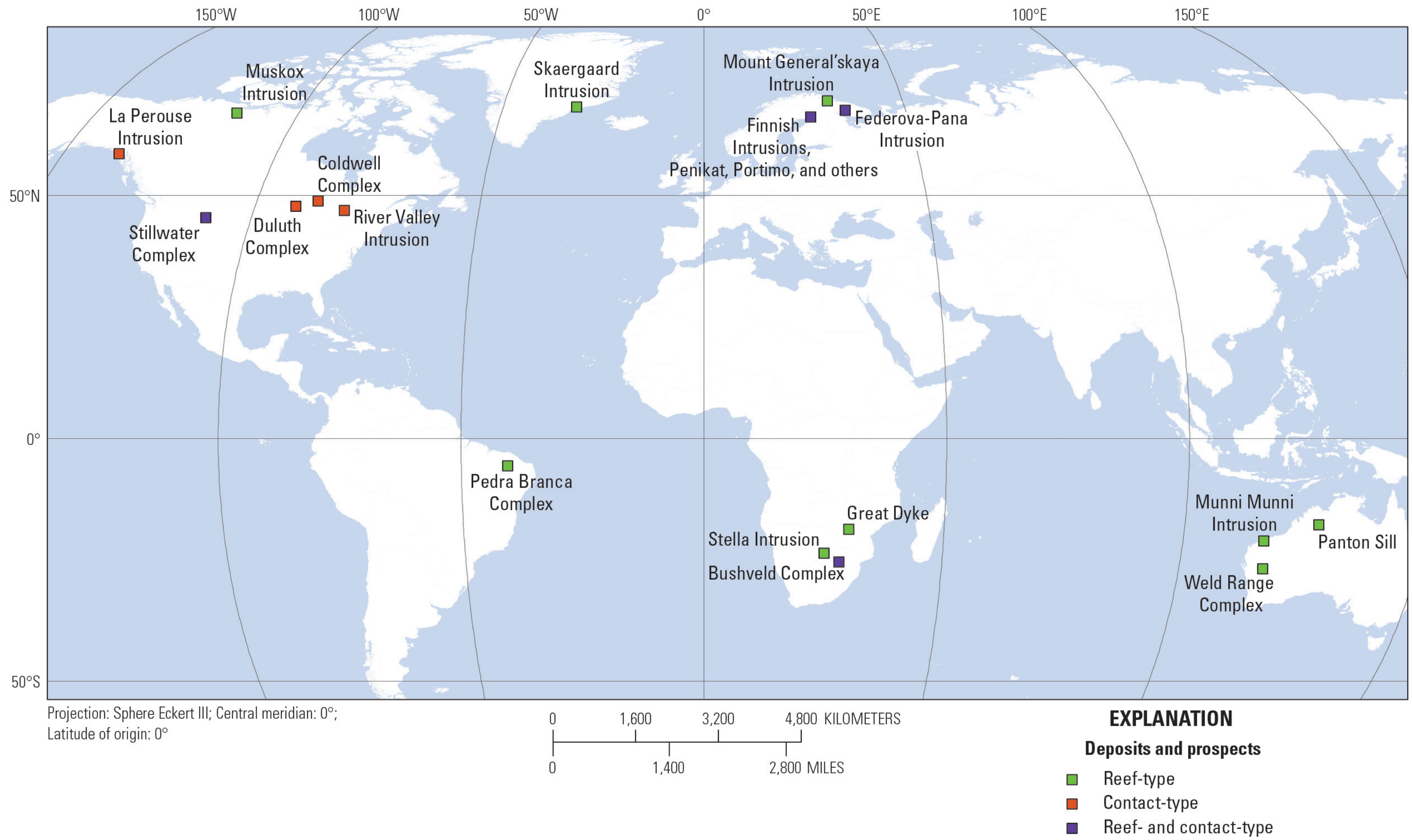

Figure 2. Map showing the location of intrusions hosting reef-type platinum-group elements (PGE) and contact-type Cu-Ni-PGE deposits.

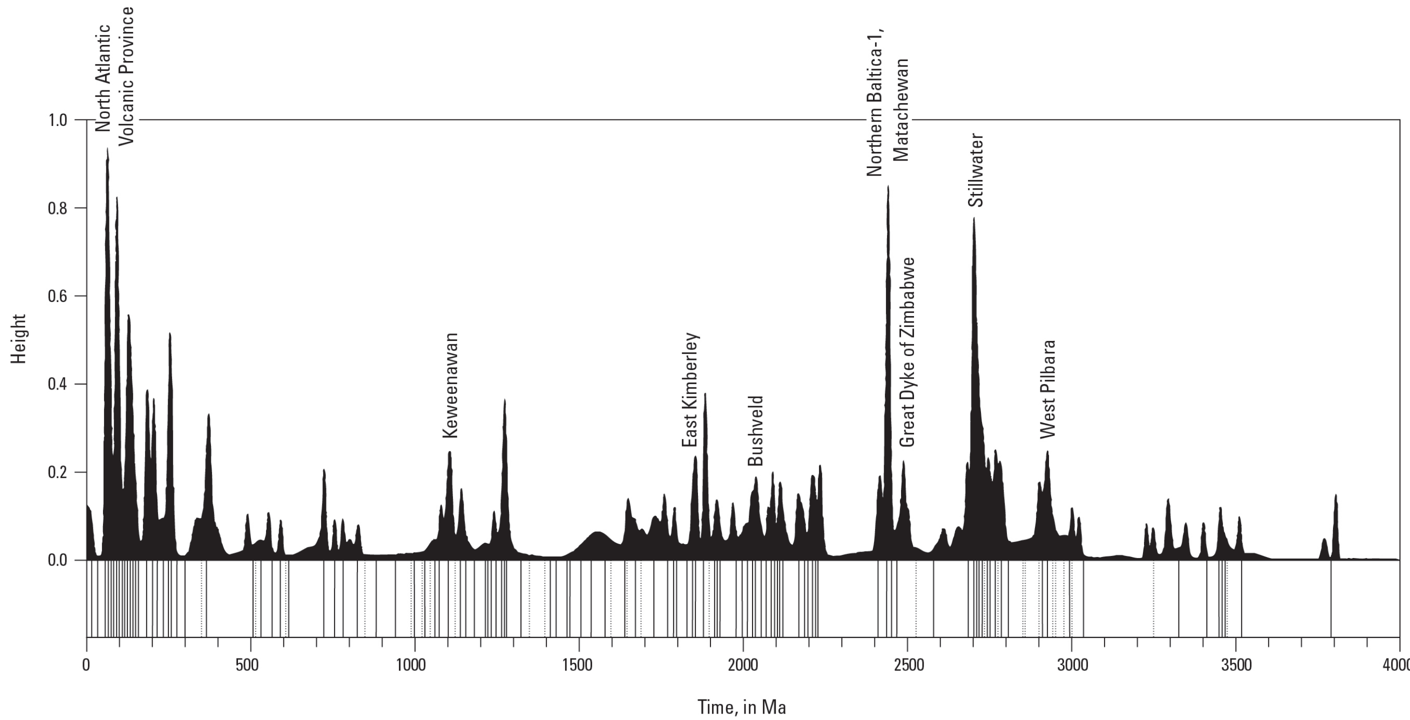

Figure 3. Chart showing the occurrence of large igneous provinces and superplume events with time. The upper curve shows a time series of superplume events versus time derived from adding Gaussians defined by ages and age errors of individual superplume proxies; height of peak is related to events with high-precision ages (Abbot and Isley, 2002). The lower bar graph shows the starting time of pulses of well-established and probable plume-head mafic-magmatic events (Ernst and others, 2005). Events that have layered igneous intrusions with reef-type platinum-group elements (PGE) and contact-type Cu-Ni-PGE deposits are labeled.

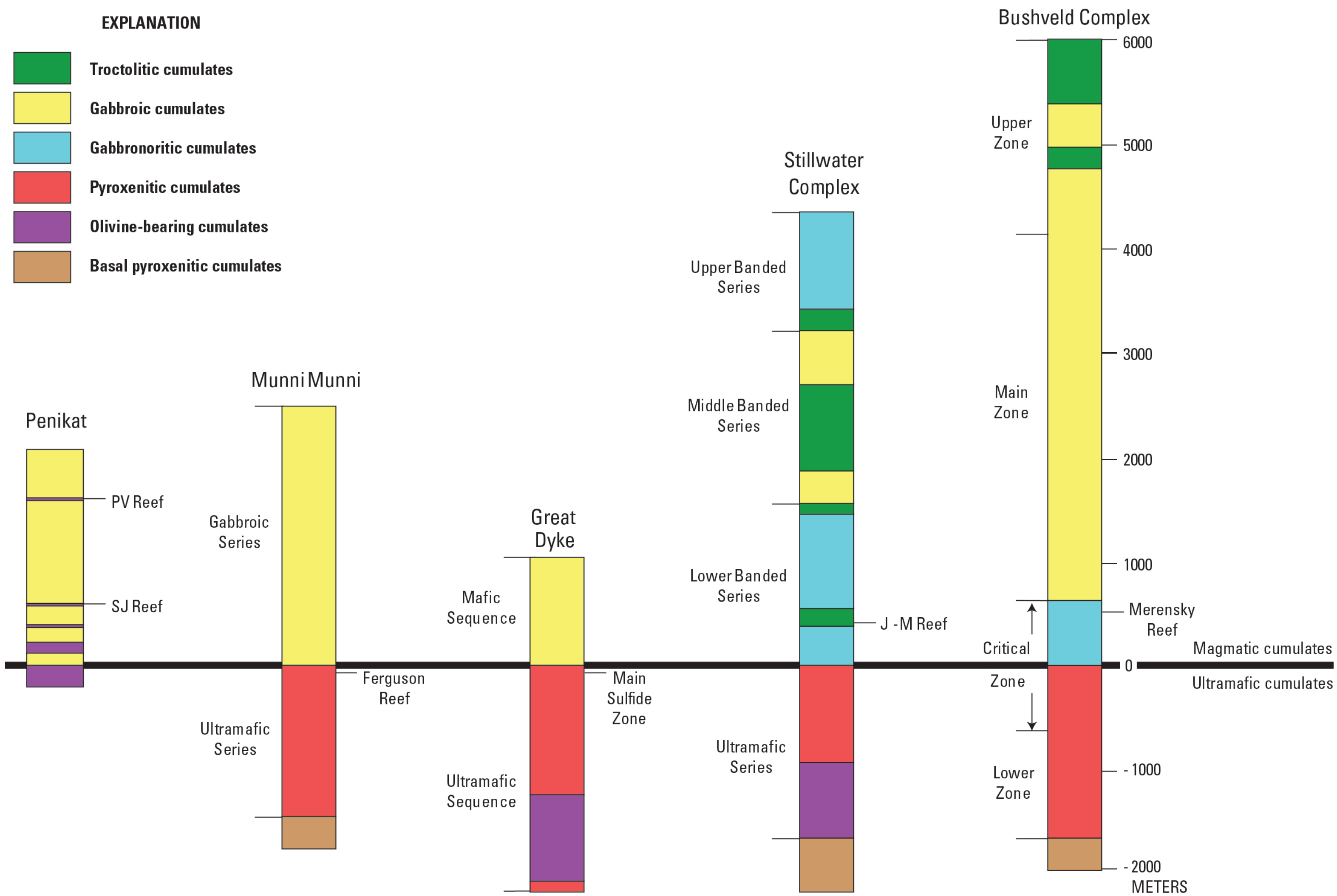

Figure 4. Columns that show the position of platinum-group elements reefs in the igneous stratigraphy of the Penikat, Munni Munni, Great Dyke, Stillwater, and Bushveld layered intrusions.

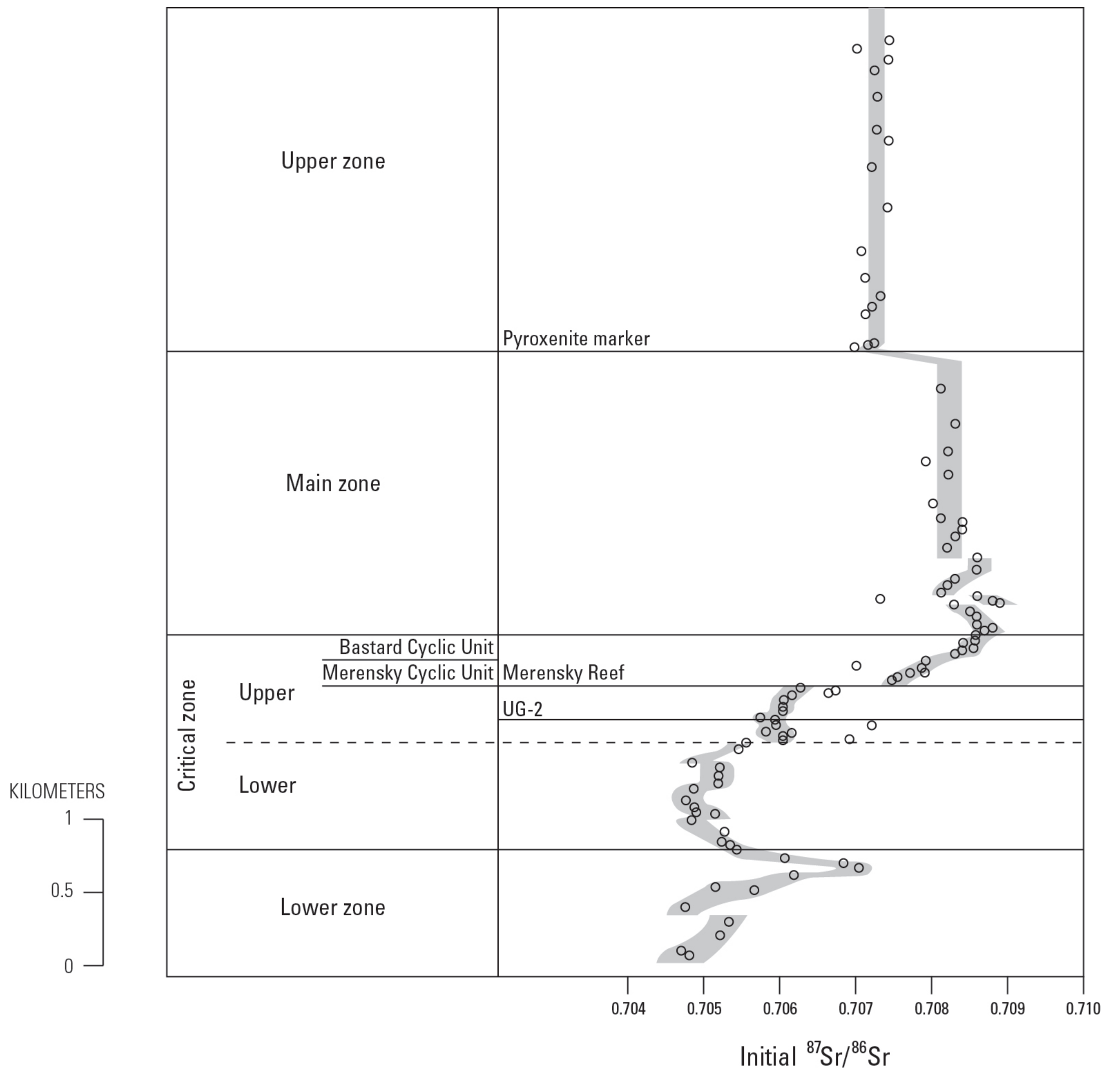

Figure 5. Stratigraphic variation of Sr isotope ratios in the Rustenburg Layered Series of the Bushveld Complex. Modified from (Kruger, 2005).

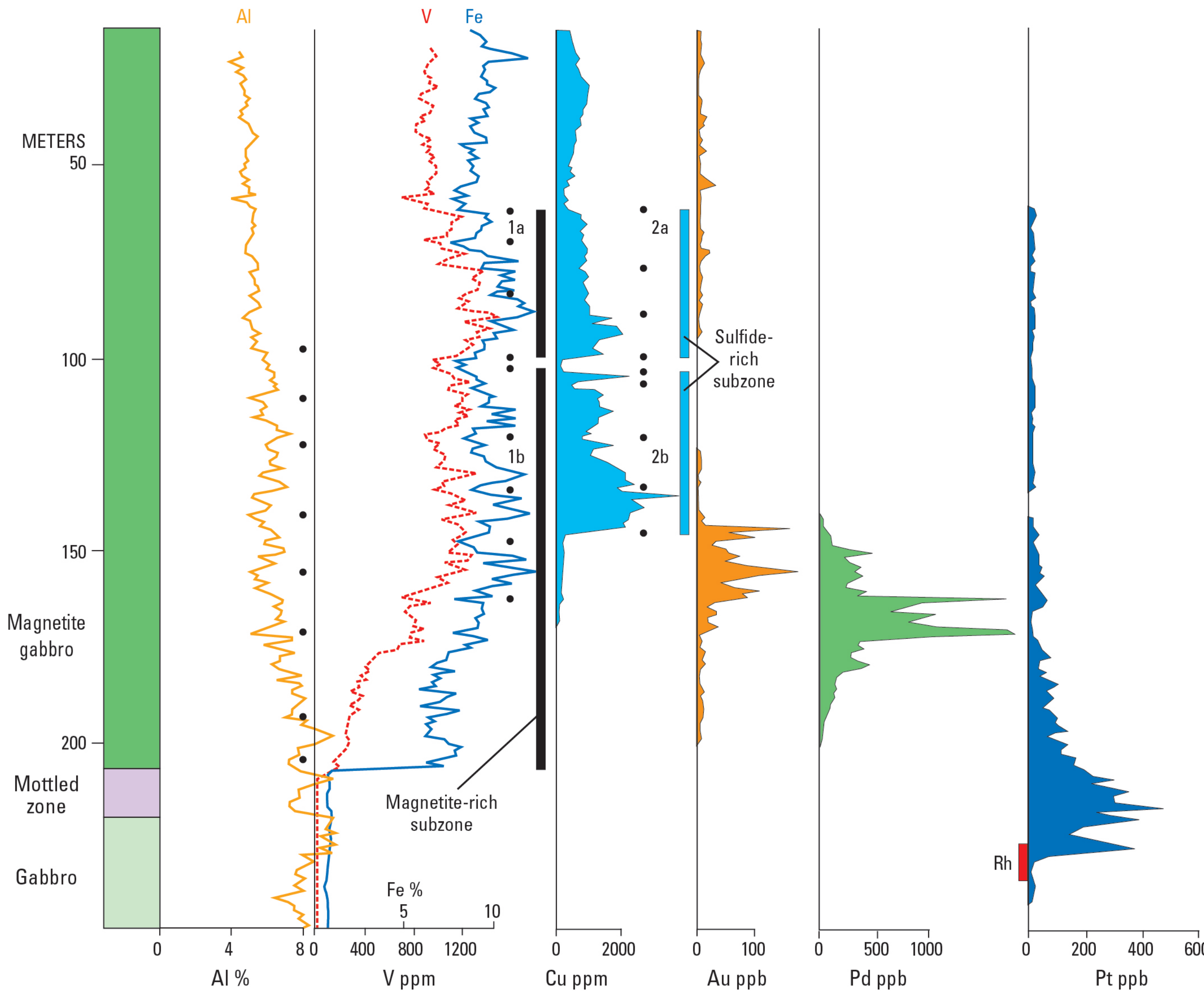

Figure 6. Stratigraphic variations in whole-rock Al, V, Fe, Cu, Au, Pd, and Pt contents in bore hole PA1 through the Precious Metals zone, Rincón del Tigre Complex, Bolivia. Modified from Prendergast (2000).

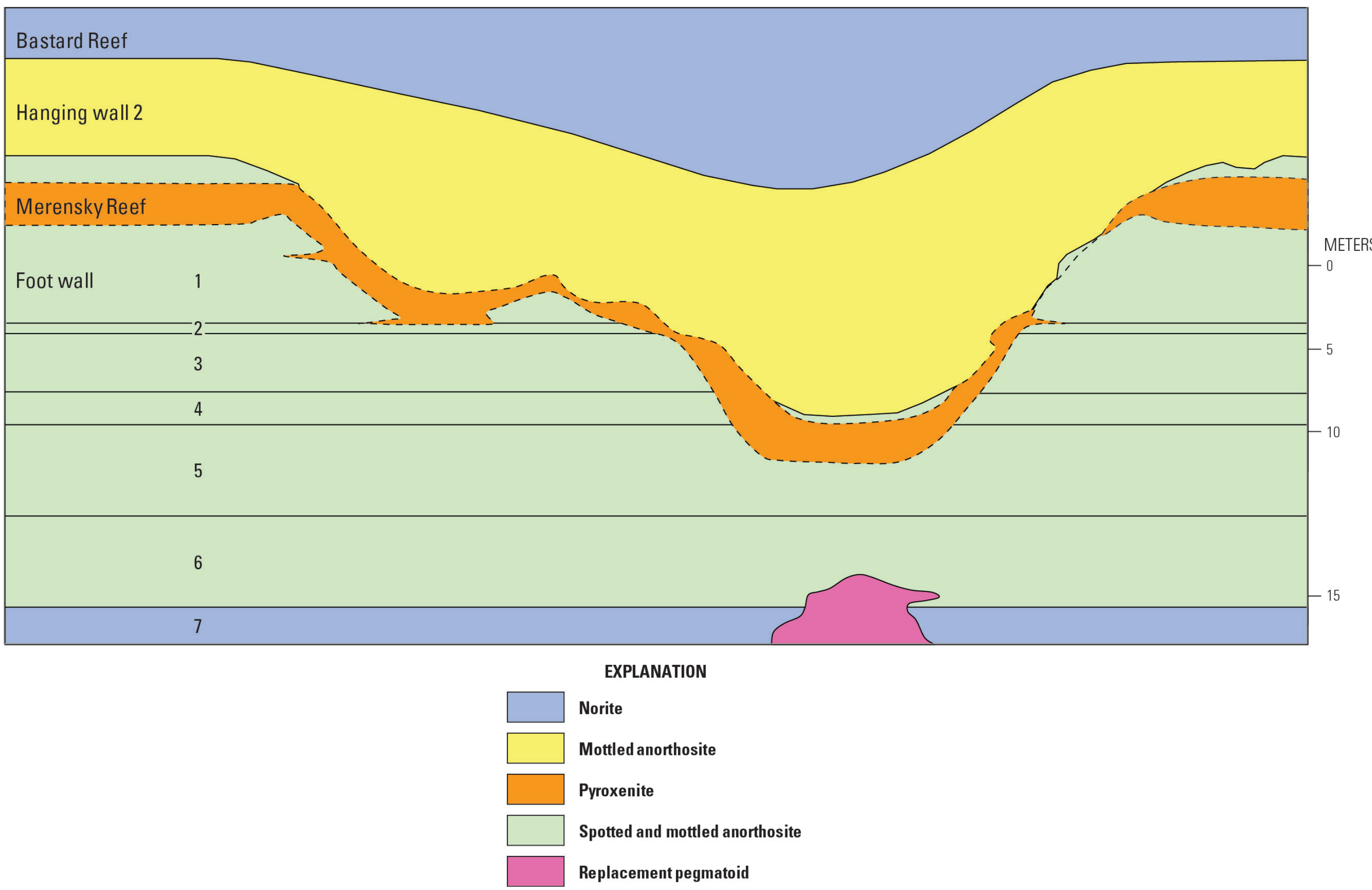

Figure 7. Section through two adjacent potholes illustrating the irregularity of the Merensky Reef, Bushveld Complex. Modified from Farquhar (1986).

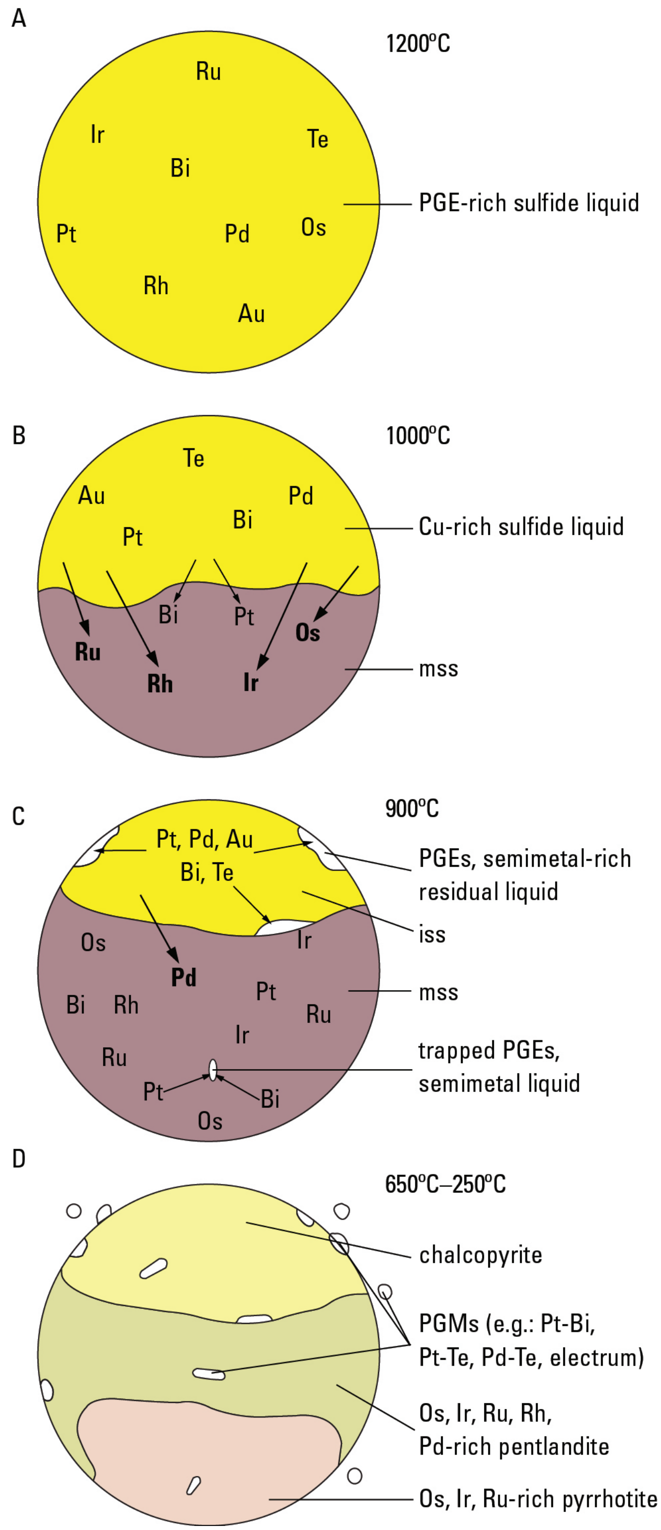

Figure 8. Schematic representation of a fractionating, platinum-group elements (PGE) enriched immiscible sulfide liquid droplet. Major partitioning behavior at each stage is emphasized by bold text. (A) Immiscible sulfide liquid. (B) Crystallization of monosulfide solid solution (mss). Os, Ir, Ru, and Rh partition into the mss phase. (C) Crystallization of intermediate solid solution (iss) from

residual sulfide liquid. Partitioning of Pt, Pd, and Au into semimetal-rich melt. Some Pd partitions into mss. (D) Recrystallization of mss to pyrrhotite and pentlandite. Rh and Pd are in solid solution in pentlandite. Crystallization of discrete platinum minerals from iss and from the residual semimetal liquid. Modified from Holwell and McDonald (2010). PGM, platinum-group minerals.

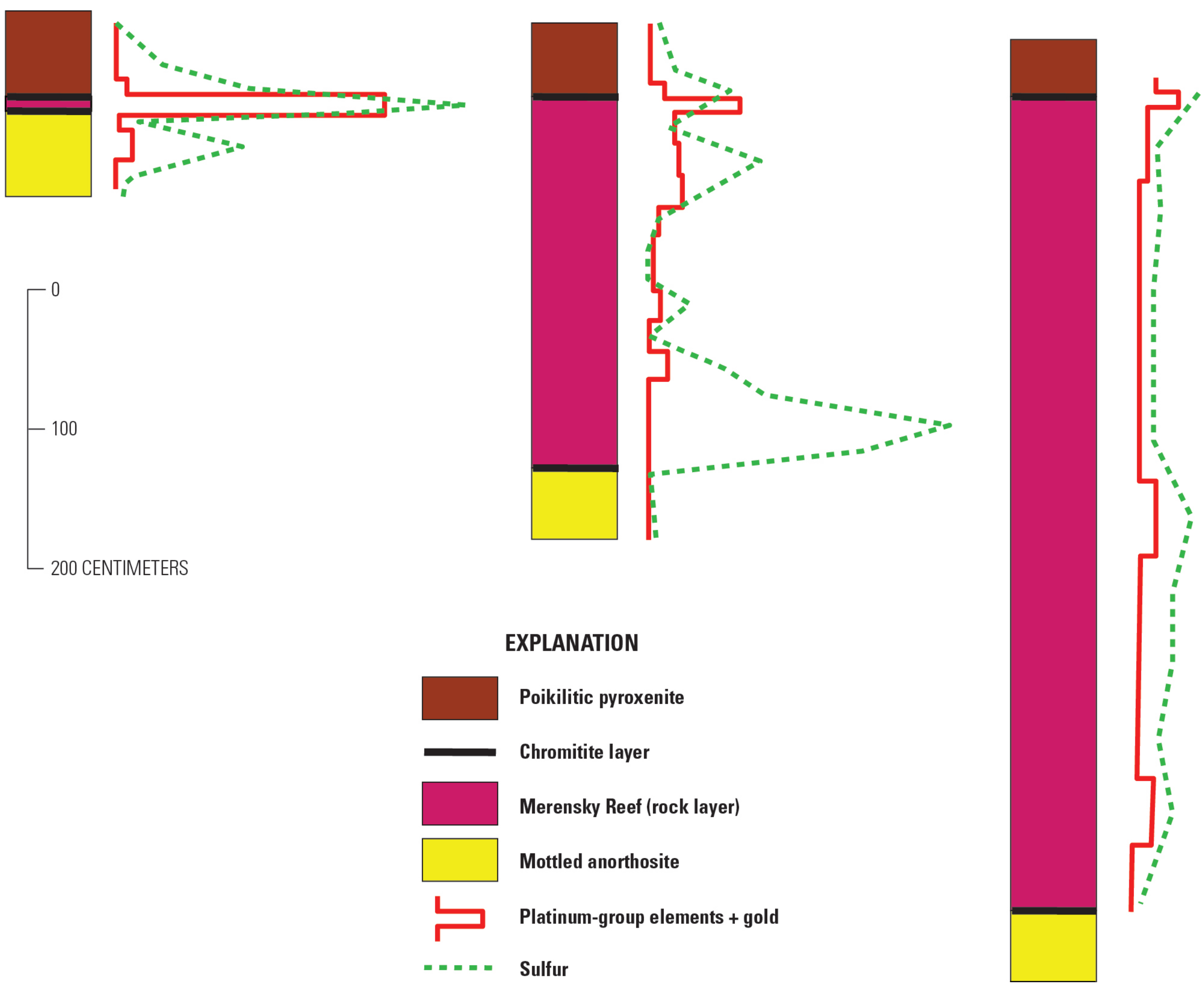

Figure 9. Variation in vertical value distribution for differing thicknesses of Merensky Reef, Amandelbult section of Rustenburg Platinum Mines. Modified from Viljoen and others (1986).

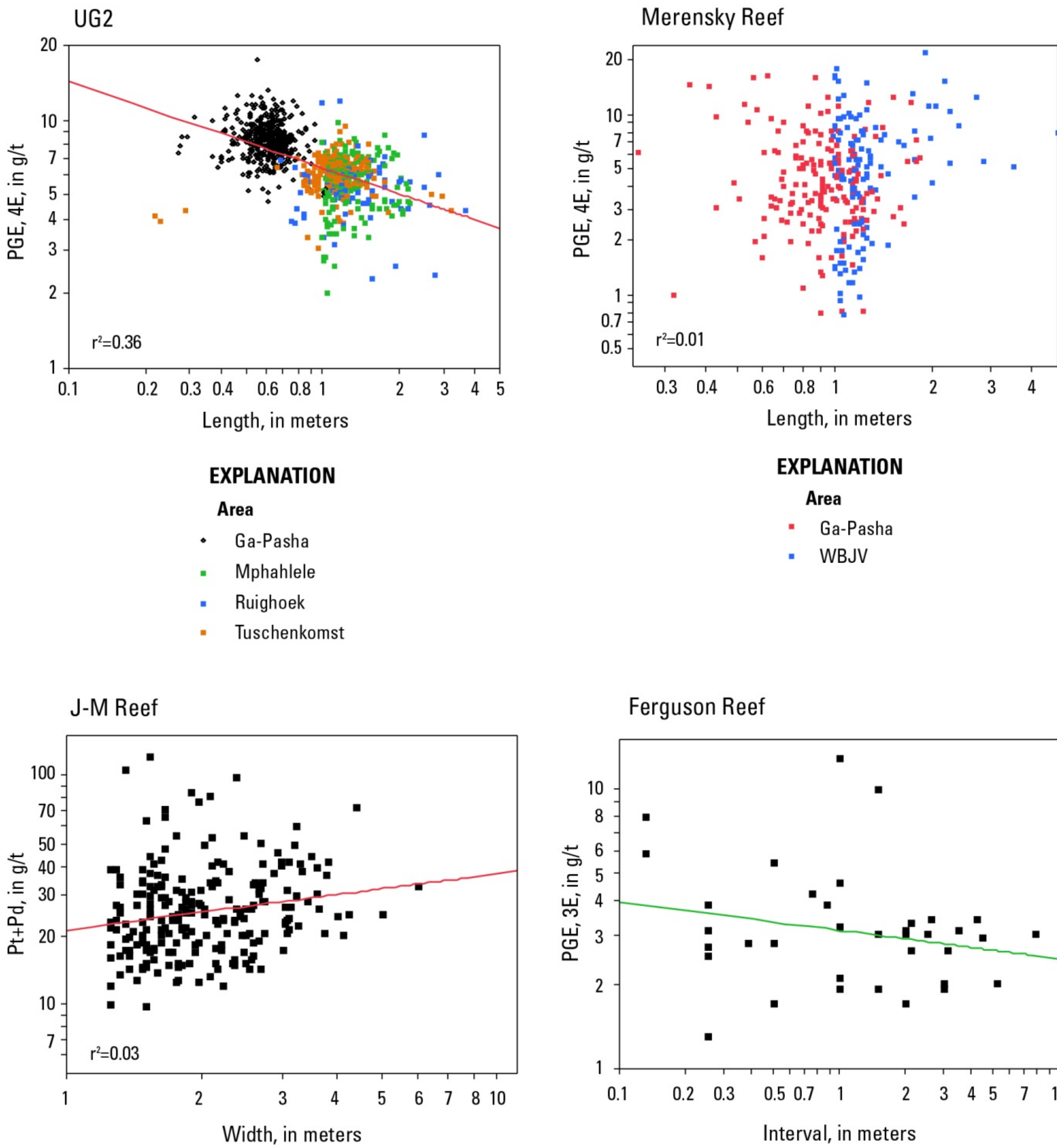

Figure 10. Bivariate plots of the combined grade of platinum, palladium, rhodium, and gold (4E) versus drill hole intercept for the UG2 chromitite and Merensky Reef, Bushveld Complex, the J-M Reef, Stillwater Complex, and the Ferguson Reef, Munni Munni Intrusion. Data are derived from company annual reports and presentations. PGE, platinum-group elements.

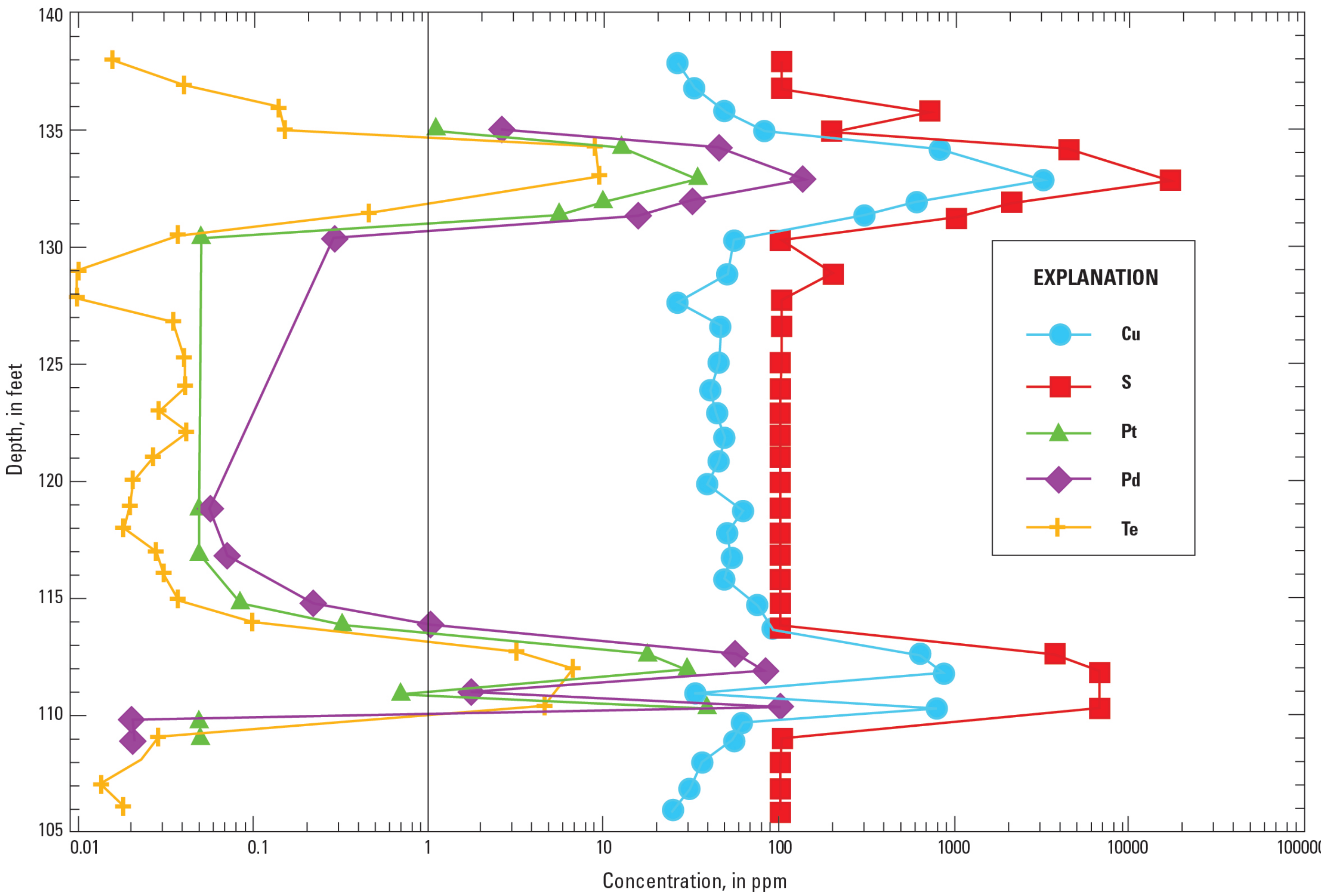

Figure 11. Profile through the J-M Reef, DDH701, 3800W stope, Stillwater Mine (Zientek and others, 1990).

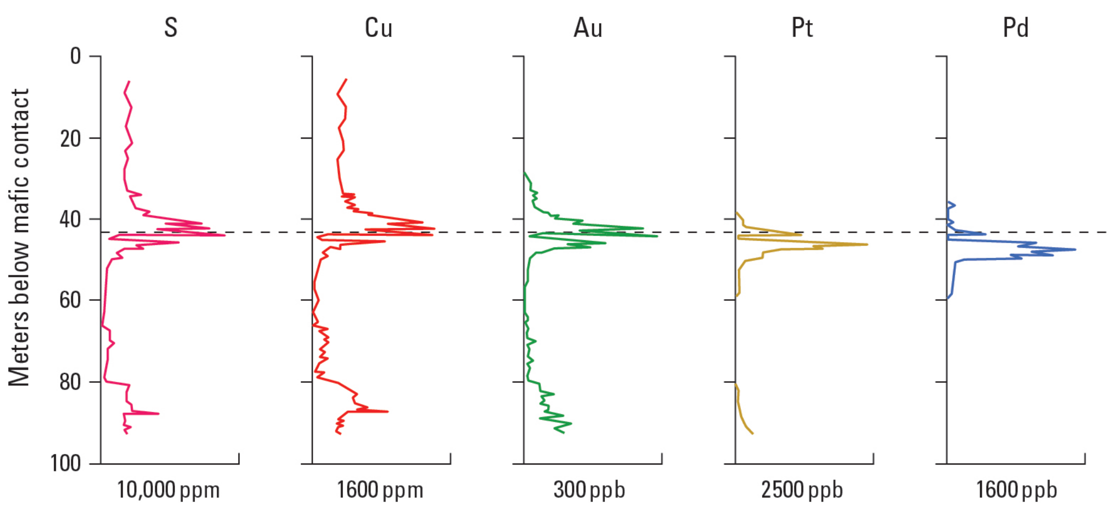

Figure 12. Vertical variation of elements through the Main Sulphide Zone in the Darwendale Subchamber of the Great Dyke, modified from Naldrett and Wilson (1990).

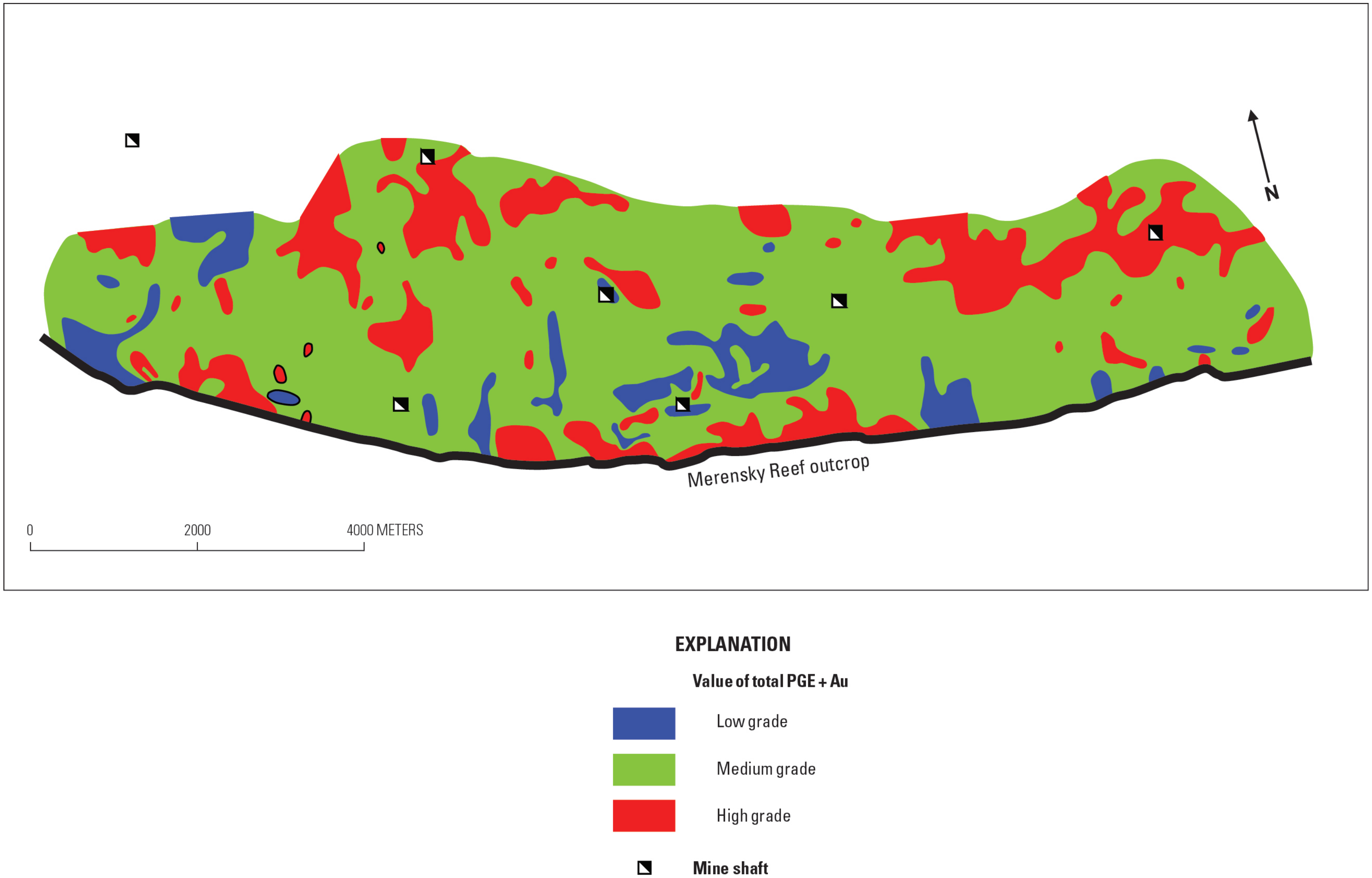

Figure 13. Value contour map of the Merensky Reef, Rustenburg section of the Rustenburg Platinum Mines. Modified from Viljoen and Hieber (1986). PGE, platinum-group elements.

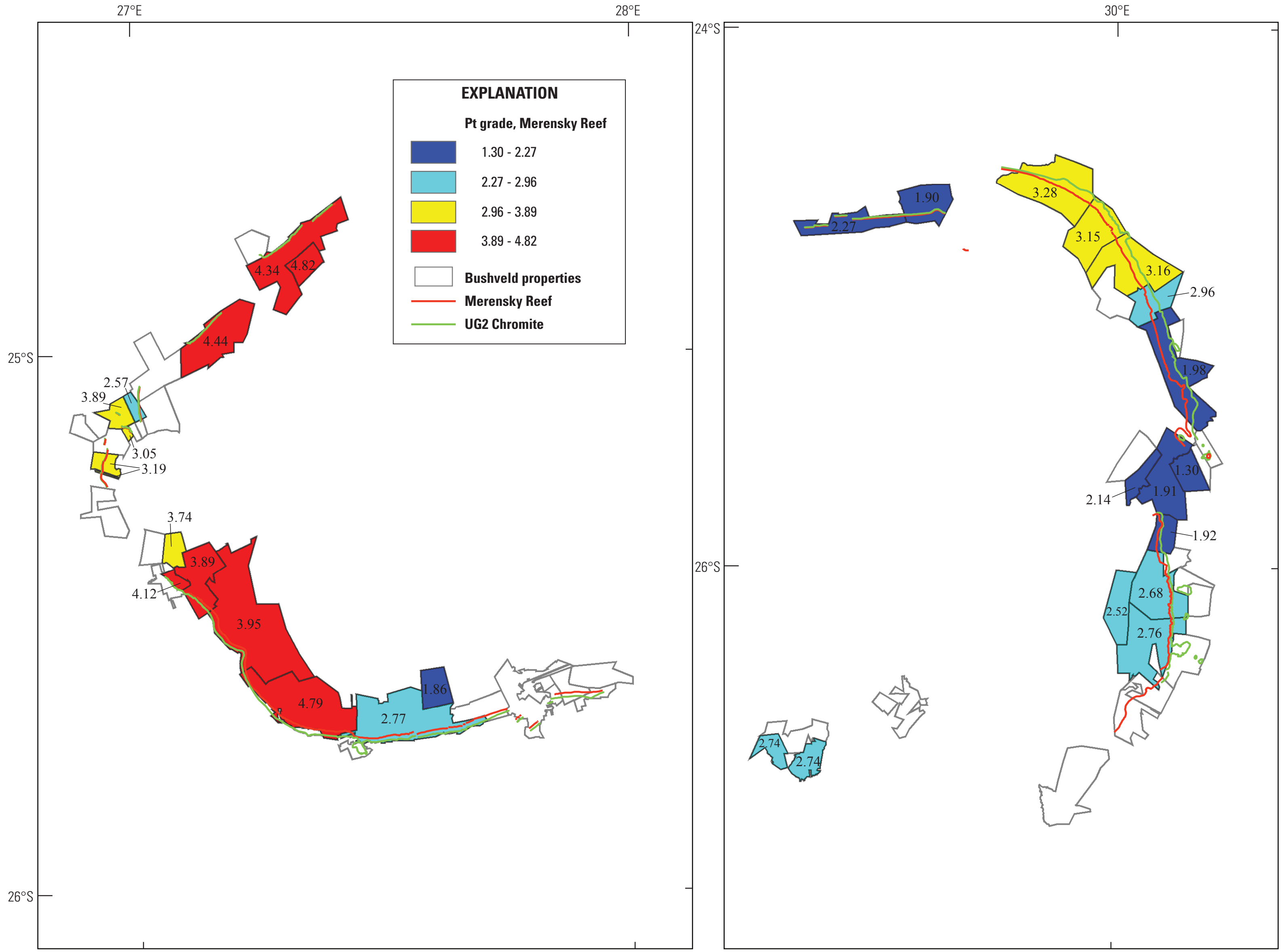

Figure 14. Map showing the outcrop trace of the Merensky Reef and its average platinum grade on mining properties in the Bushveld Complex. Data are derived from company annual reports and presentations and are current as of 2006.

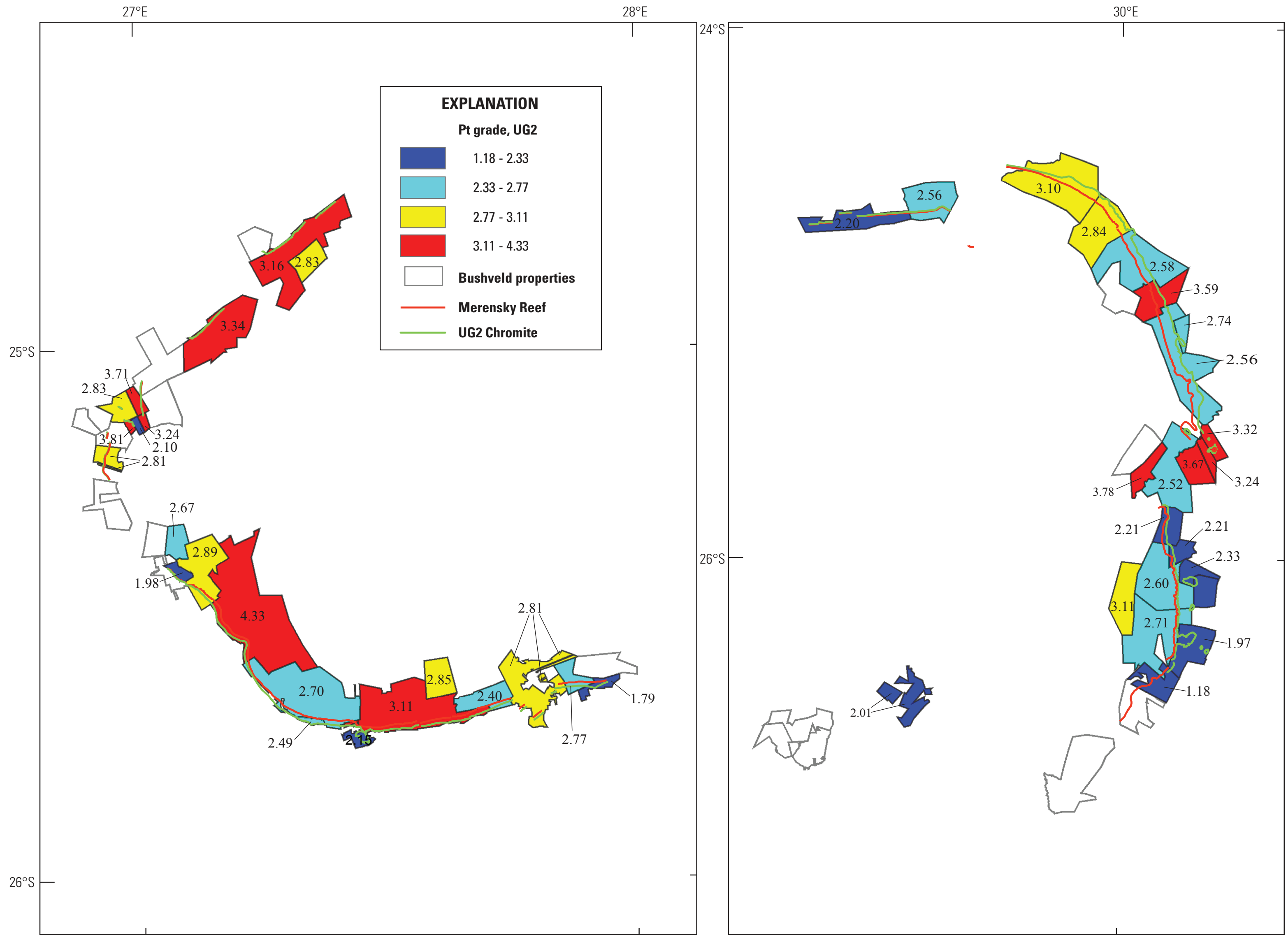

Figure 15. Map showing the outcrop trace of the UG2 chromitite and its average platinum grade on mining properties in the Bushveld Complex. Data are derived from company annual reports and presentations and are current as of 2006.

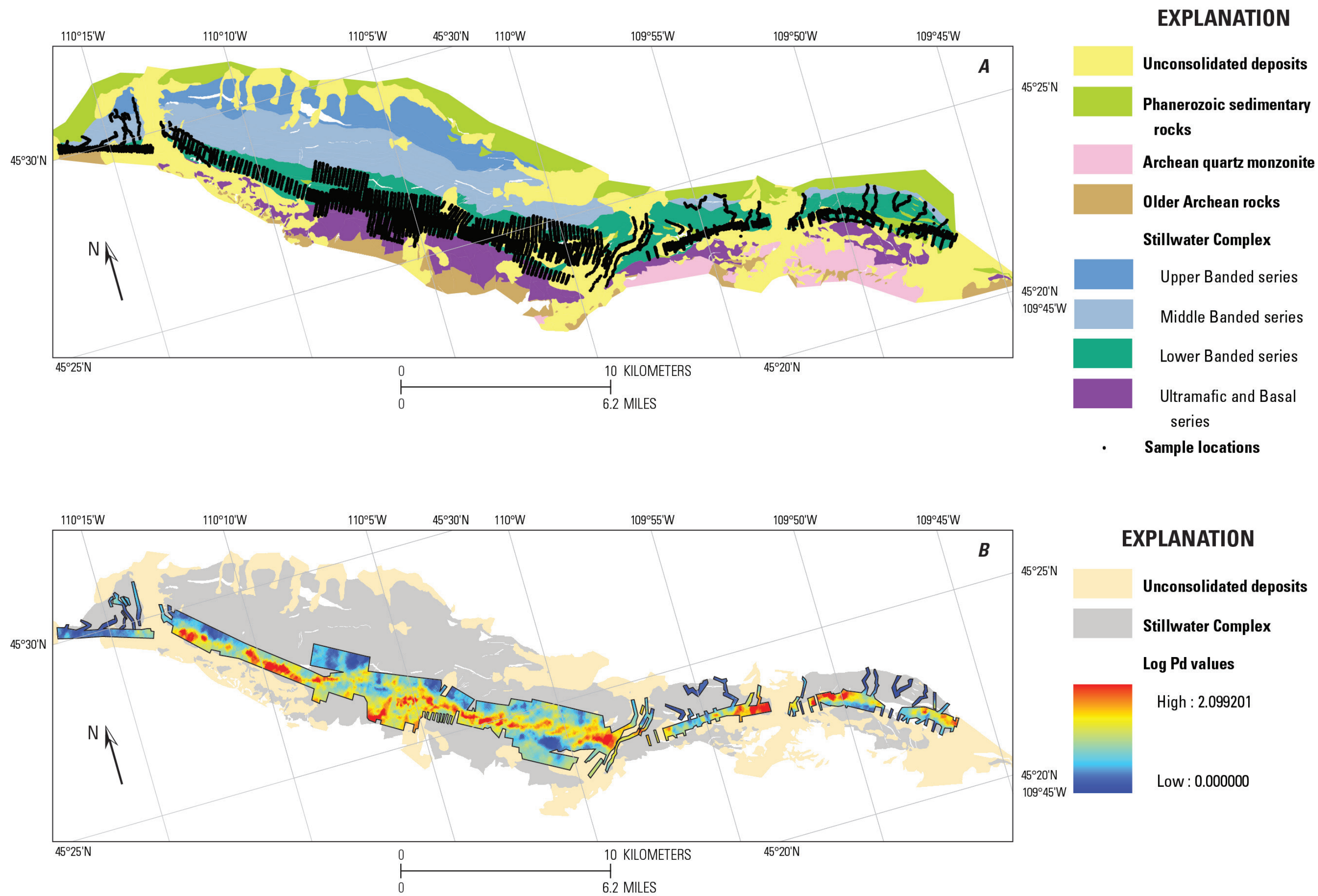

Figure 16. Maps showing the distribution and results of soil and talus fines geochemistry surveys in relation to the geology of the Stillwater Complex. (A) Location of talus and soil samples on map showing series level subdivisions of the Stillwater Complex. (B) Surface of log palladium values generated from sample data shown relative to the Stillwater Complex and unconsolidated deposits (Zientek and others, 2005).

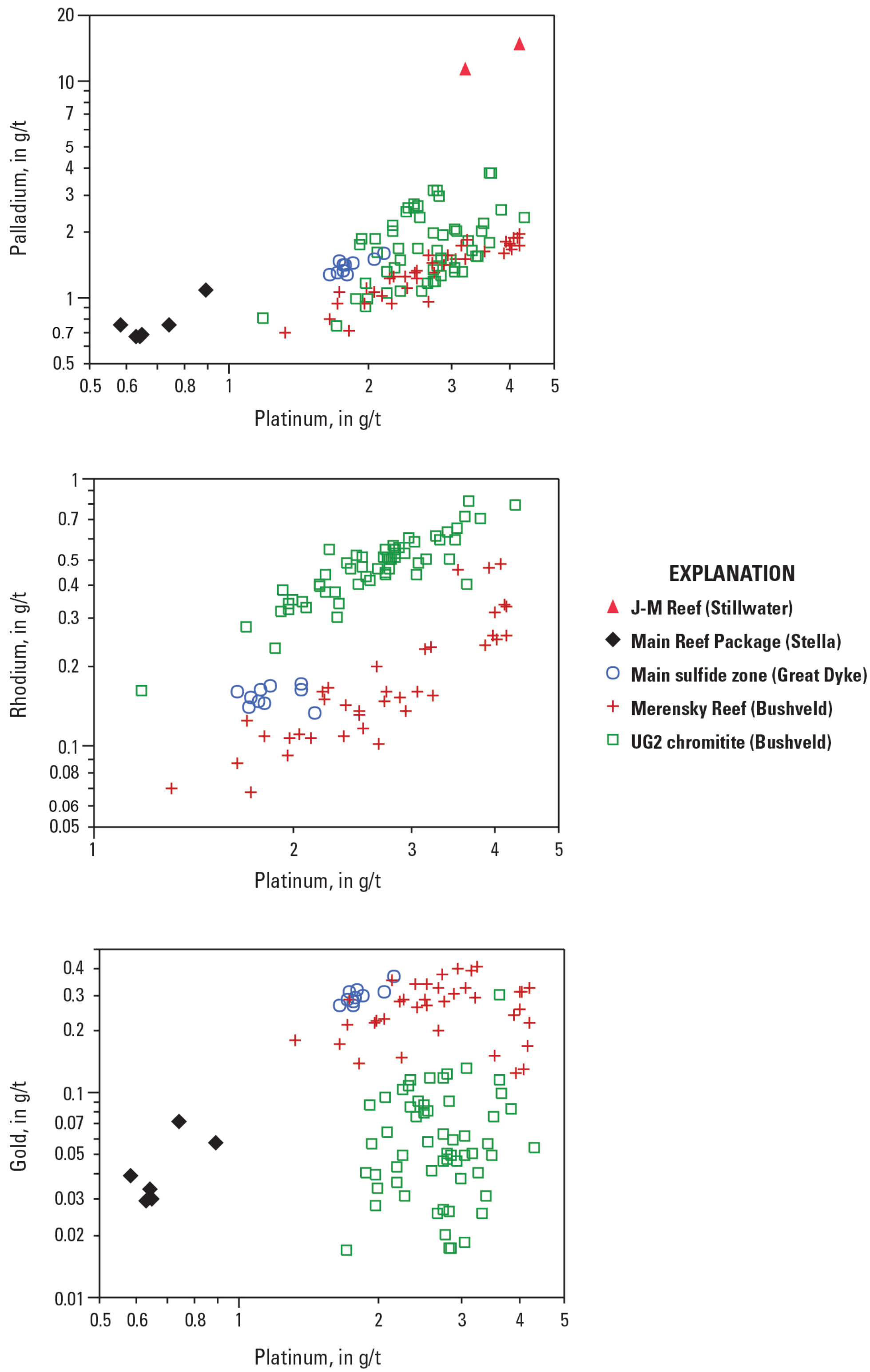

Figure 17. Bivariate plots of the average grade of palladium, rhodium, and gold versus average platinum grade for mines and mineral properties on the Stillwater, Stella, and Bushveld layered igneous intrusions. Data are derived from company annual reports and presentations and are current as of 2009.

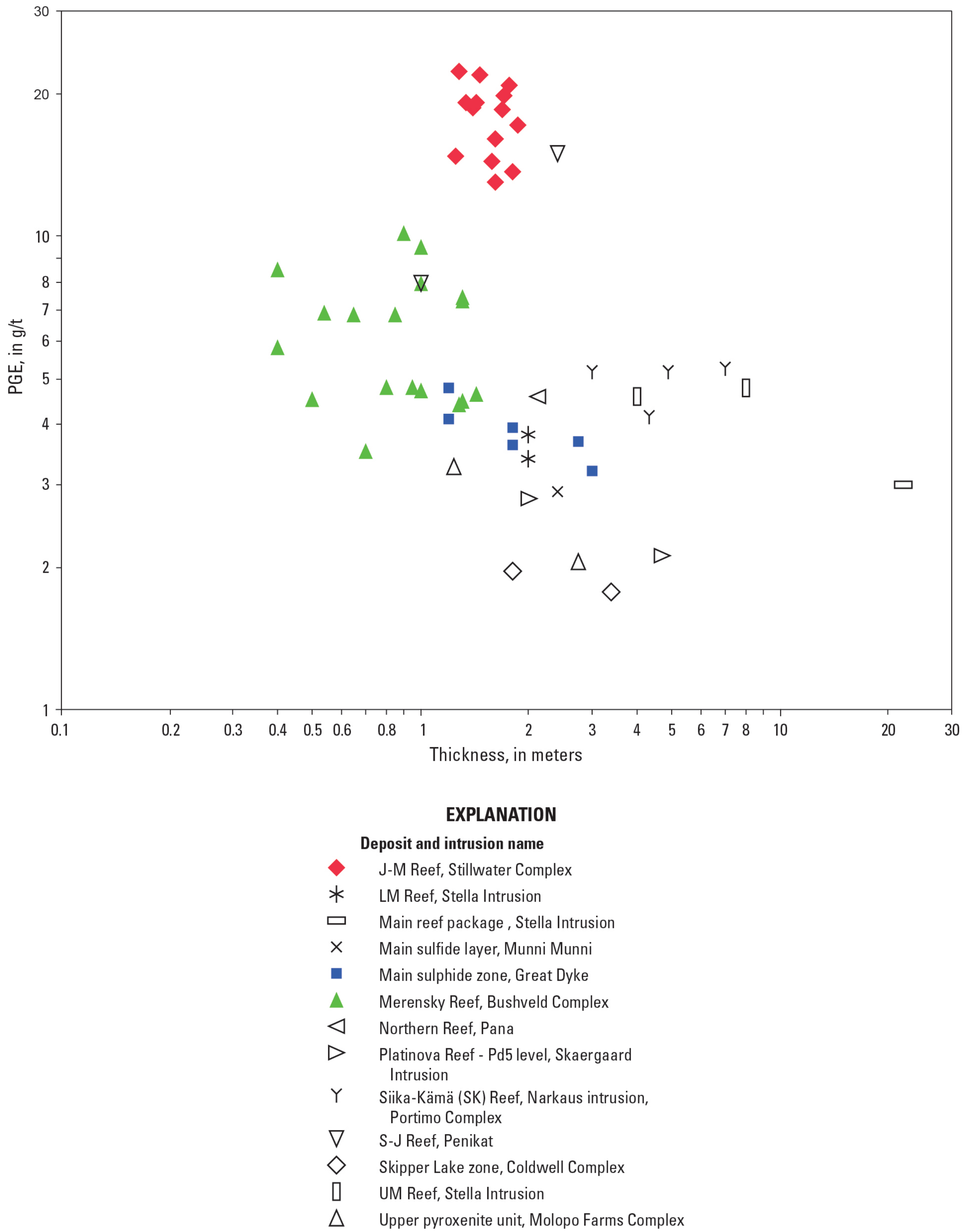

Figure 18. Bivariate plot of the average platinum-group elements (PGE) grade versus mineralized layer thickness for PGE reef-type deposits.

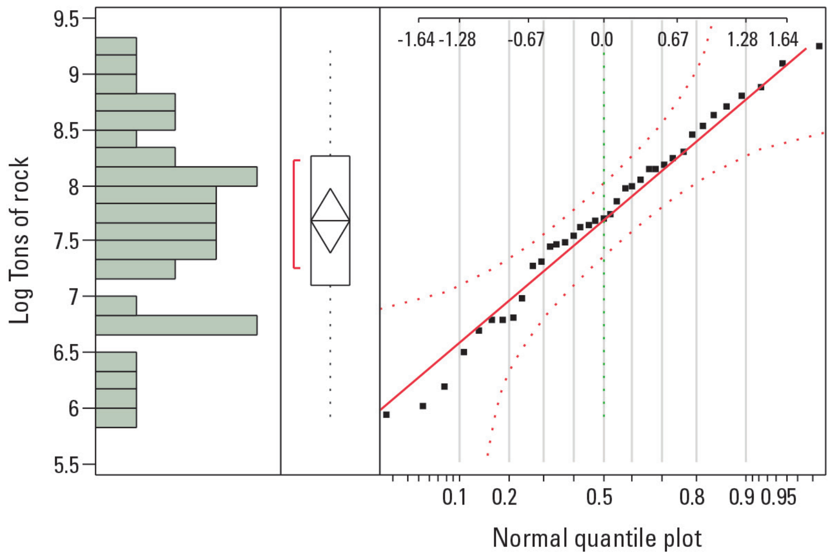

Figure 19. Histograms, box plots, and normal quantile plots illustrating distribution of tonnage of rock in contact-type deposits.

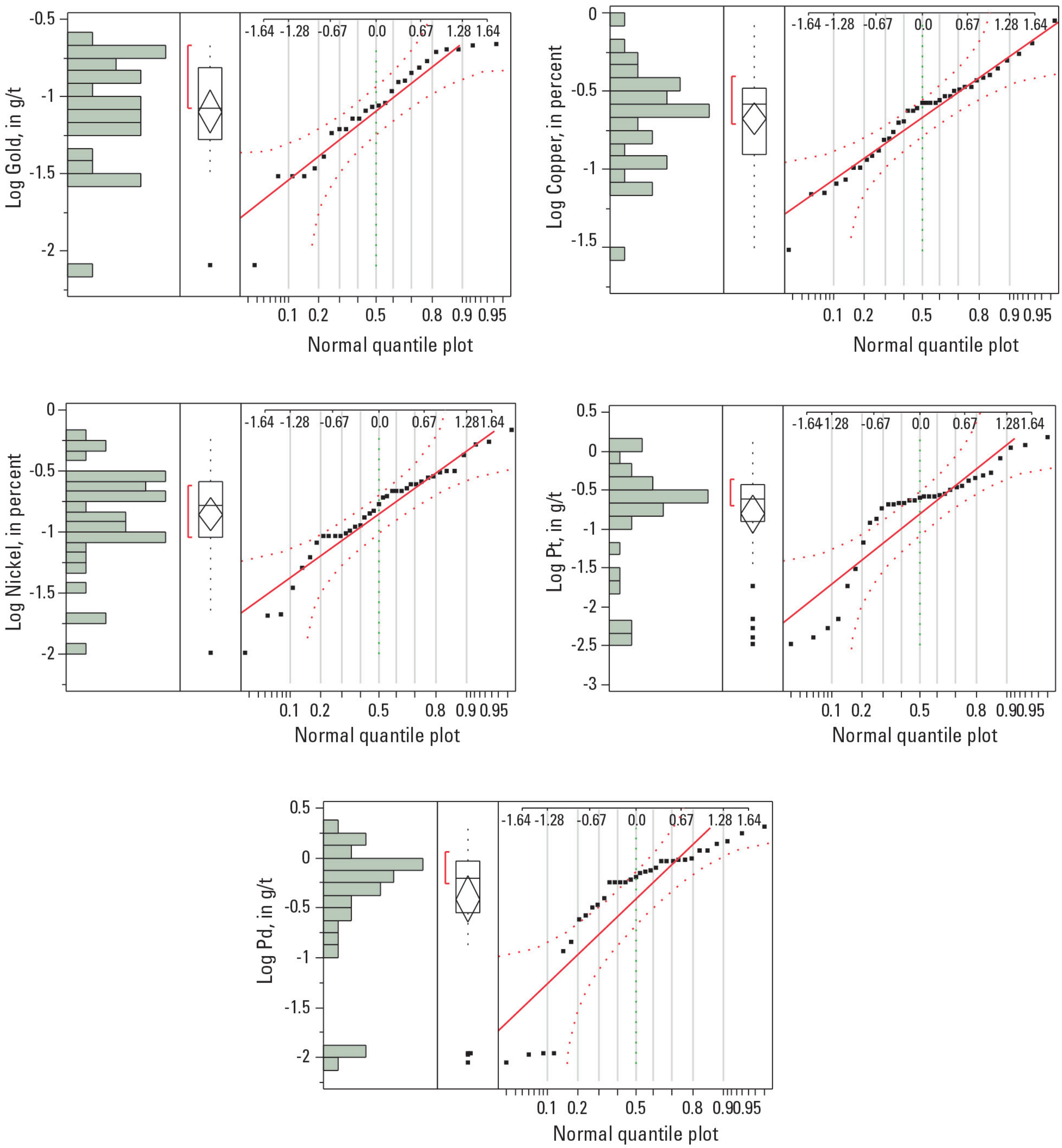

Figure 20. Histograms, box plots, and normal quantile plots illustrating distribution of copper, nickel, platinum, palladium, and gold in contact-type deposits.

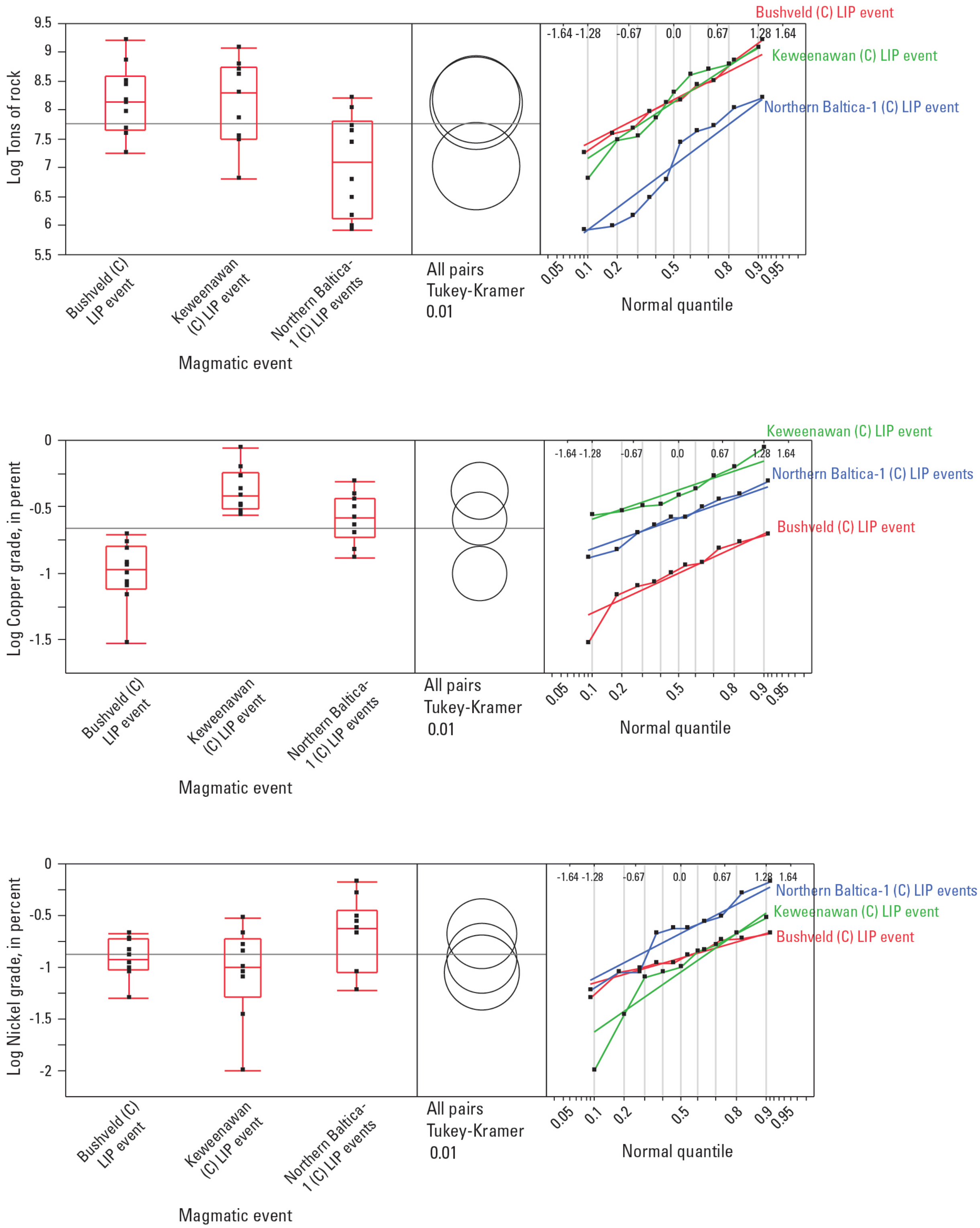

Figure 21. Box plots, comparison circles, and normal quantile plots comparing distribution of tonnage, copper grade, and nickel grade between deposits associated with the Bushveld, Keewenawan, and Baltica large igneous province (LIP) events. The letter (C) is a rating indicating that the event is possibly linked to a mantle plume head (Ernst and Buchan, 2001).

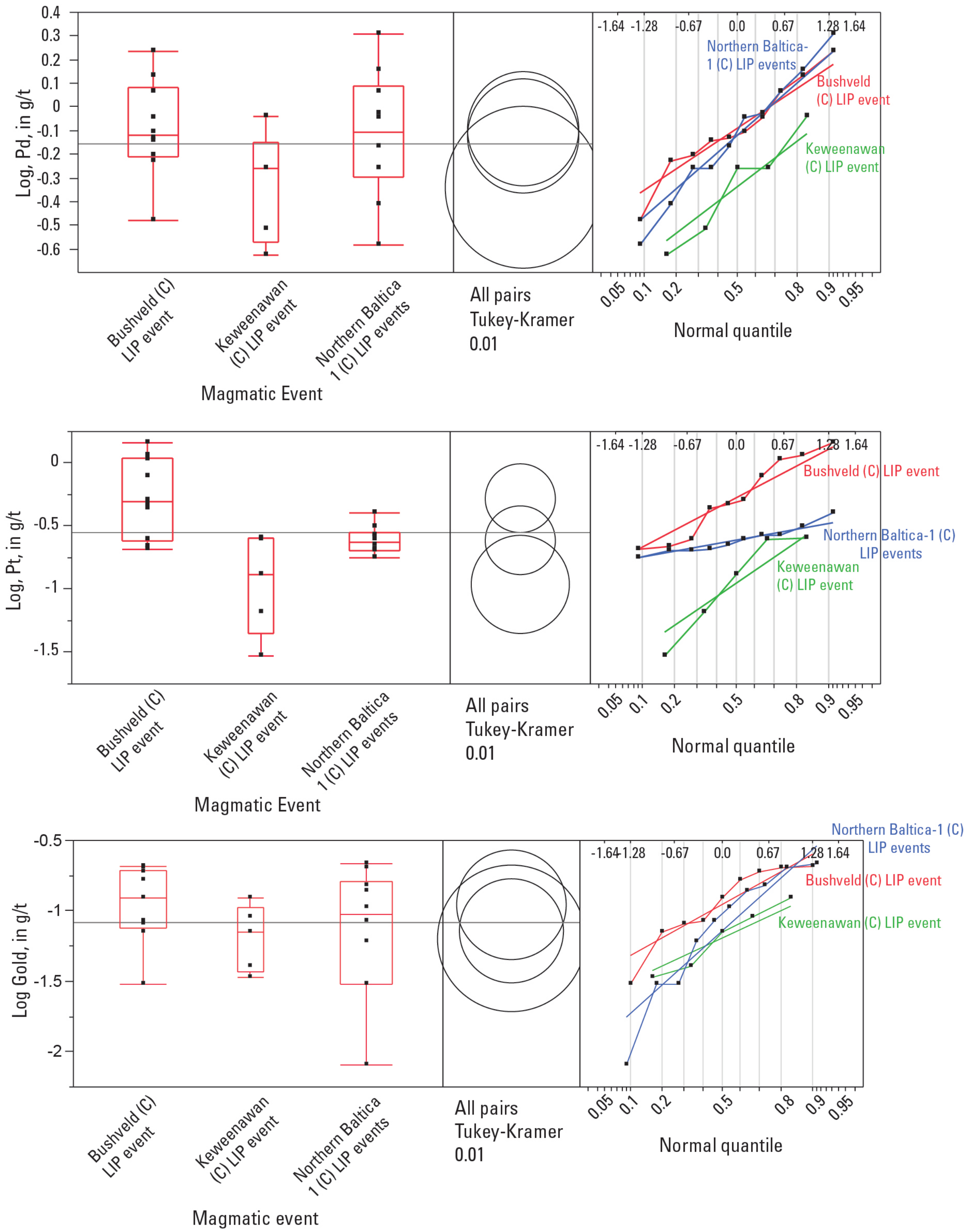

Figure 22. Box plots, comparison circles, and normal quantile plots comparing distribution of palladium (Pd), platinum (Pt), and gold grade between deposits associated with the Bushveld, Keewenawan, and Baltica large igneous province (LIP) events. The letter (C) is a rating indicating that the event is possibly linked to a mantle plume head (Ernst and Buchan, 2001).

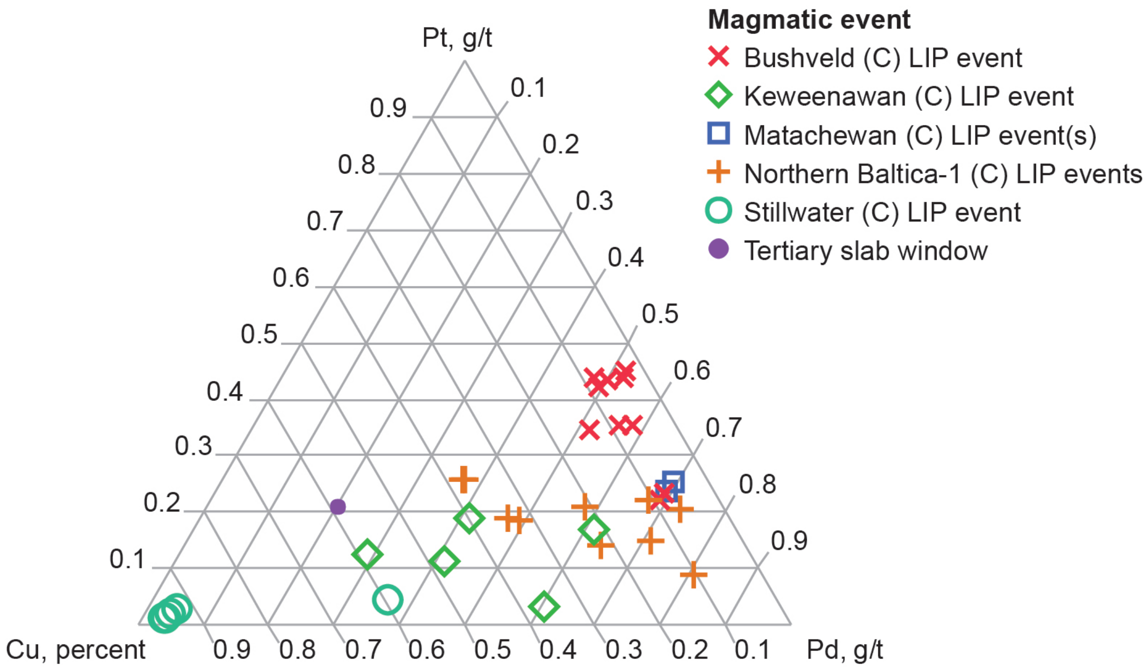

Figure 23. Ternary plot showing the proportion of copper, platinum, and palladium in contact-type deposits. LIP, large igneous province. The letter (C) is a rating indicating that the event is possibly linked to a mantle plume head (Ernst and Buchan, 2001).

Table 1. The platinum group elements, their atomic numbers, chemical symbols, and value.

Element	Atomic number	Chemical symbol	Price, U.S. $ per oz
Platinum	78	Pt	1,820.78
Palladium	46	Pd	739.18
Rhodium	45	Rh	1,863.36
Ruthenium	44	Ru	169.38
Iridium	77	Ir	1,068.57
Osmium	76	Os	380.00

Table 2. Tonnage and grade characteristics of reserves and resources associated with reef-type platinum-group elements deposits. Past production is not included. Large igneous province (LIP) names and ratings from Ernst and Buchan (2001).

Magmatic event	LIP Rating	Approximate age (Ma)	Deposit name	Intrusion	Area	Country	Date of estimate	Resource category	Tons of ore	Ni, percent	Cu, percent	Pt, g/t	Pd, g/t	Rh, g/t	Au, g/t	Pt+Pd+Au, g/t	"PGE" ± Au, g/t	References
Bushveld (C) LIP event	A (1s)	2054	Merensky Footwall Reef	Bushveld Complex	BV-Western Limb	RSA	2009	Reserves and measured, indicated, and inferred resources	26,182,000			0.6161	0.2828	0.0606	0.0505		1.01	D. Causey, written comm., 2009
Bushveld (C) LIP event	A (1s)	2054	Merensky Reef	Bushveld Complex		RSA	1999	Proven and probable reserves and inferred resources	4,987,800,000			3.279572276	1.762486547				5.042058824	Cawthron (1999)
Bushveld (C) LIP event	A (1s)	2054	Merensky Reef	Bushveld Complex	BV-Eastern and Western Limb	RSA	2009	Reserves and measured, indicated, and inferred resources	3,733,344,220			2.906020937	1.428774501	0.203193246	0.2664378		4.804426483	D. Causey, written comm., 2009
Bushveld (C) LIP event	A (1s)	2054	PGE Reefs (undifferentiated)	Bushveld Complex	BV-Western Limb	RSA	2009	Reserves and measured, indicated, and inferred resources	114,745,000			3.188030038	1.541009335	0.425946319	0.119434734		5.274420427	D. Causey, written comm., 2009
Bushveld (C) LIP event	A (1s)	2054	Pseudo Reef Harzburgite	Bushveld Complex	BV-Western Limb	RSA	2009	Reserves and measured, indicated, and inferred resources	19,554,000			0.531	0.279	0.036	0.054		0.9	D. Causey, written comm., 2009
Bushveld (C) LIP event	A (1s)	2054	Lower Pseudo Reef	Bushveld Complex	BV-Western Limb	RSA	2009	Reserves and measured, indicated, and inferred resources	8,846,800			1.519225311	0.712740496	0.209633251	0.072927456		2.514526513	D. Causey, written comm., 2009
Bushveld (C) LIP event	A (1s)	2054	Upper Pseudo Reef	Bushveld Complex	BV-Western Limb	RSA	2009	Reserves and measured, indicated, and inferred resources	6,539,800			2.118700244	1.036587849	0.170537053	0.138449323		3.464274469	D. Causey, written comm., 2009
Bushveld (C) LIP event	A (1s)	2054	Sheba's Ridge	Bushveld Complex	BV-Eastern Limb	RSA	2009	Reserves and measured, indicated, and inferred resources	775,000,000			0.175301548	0.541148258		0.045730839		0.762180645	D. Causey, written comm., 2009
Bushveld (C) LIP event	A (1s)	2054	UG2	Bushveld Complex		RSA	1999	Proven and probable reserves and inferred resources	6,250,600,000			2.84299648	2.322447829				5.165444309	Cawthron (1999)
Bushveld (C) LIP event	A (1s)	2054	UG2	Bushveld Complex	BV-Eastern and Western Limb	RSA	2009	Reserves and measured, indicated, and inferred resources	6,636,236,713			2.701973524	1.834189128	0.496749709	0.059239758		5.092152119	D. Causey, written comm., 2009
Bushveld (C) LIP event	A (1s)	2054	Upper Mineralized Pyroxentite (Merensky Reef?)	Bushveld Complex	BV-Western Limb	RSA	2009	Reserves and measured, indicated, and inferred resources	24,730,000			2.546652337	1.212691589		0.267656866		4.027000793	D. Causey, written comm., 2009
Bushveld (C) LIP event	A (1s)	2054	Platreef	Bushveld Complex		RSA	1999	Proven and probable reserves and inferred resources	2,274,600,000			2.199211905	2.220314693				4.419526598	Cawthron (1999)
Great Dyke of Zimbabwe (C) event	B (5)	2575	Main sulphide zone	Great Dyke		Zimbabwe	2009	Reserves and measured, indicated, and inferred resources	2,135,592,000			1.792530963	1.433275106	0.150328009	0.30105269		3.677186768	D. Causey, written comm., 2009
North Atlantic Magmatic Province		55.65	Platinova Au-Pd Reef	Skaergaard		Greenland	2005	Inferred resource	1,520,000,000			0.04	0.61		0.21		0.86	Platina Resources, Ltd. (2010b)
Stillwater (C) LIP event	B (4i)	2704	A-B chromite, West Fork area	Stillwater Complex		USA	1979	Resource	3,600,000			0.685	1.714				2.399	Zientek (1993)
Stillwater (C) LIP event	B (4i)	2704	J-M Reef	Stillwater Complex		USA	2010	Reserves and mineralized material	149,398,000			3.68067246	12.88235361				16.56302607	Abbott and others (2011)
		3033	Main Reef Package	Stella layered intrusion		RSA	2009	Reserves and measured, indicated, and inferred resources	133,302,579			0.685426928	0.779251463		0.042220011		1.506898401	D. Causey, written comm., 2009
			Weld Range - Parks Reef PGE	Weld Range		Australia	1998	Inferred resource	14,760,000			0.6	0.5				1.1	Parks (1998)
West Pilbara (C) event	B (4i)	2935	Main sulfide layer (Ferguson Reef)	Munni Munni		Australia	2002	Measured, indicated, and inferred resources	23,600,000	0.09	0.15	1.1	1.5	0.1	0.2		2.9	Platina Resources, Ltd. (2010a)
East Kimberley (C) events	B (4vid)	1856	Top and Middle Reefs	Panton Sill		Australia	2003	Measured, indicated, and inferred resources	14,300,000	0.3	0.08	2.2	2.4		0.3		5.2	Platinum Australia (2003)
Northern Baltica-1 (C) LIP events	A (1v)	2440	Siika-Kämä Reef	Narkaus Intrusion		Finland	2003	Measured, indicated, and inferred resources	43,100,000	0.08	0.21	0.72	2.7		0.11		3.53	Geological Survey of Finland (2010)
Northern Baltica-1 (C) LIP events	A (1v)	2440	Sompujärvi Reef	Penikat Intrusion		Finland			6,700,000			3.08	5.36	0.38	0.1		8.92	Geological Survey of Finland (2010)
Northern Baltica-1 (C) LIP events	A (1v)	2440	Paasivaara Reef	Penikat Intrusion		Finland			5,000,000		0.28	4.04	2.58	0.08	0.61		7.31	Geological Survey of Finland (2010)
		2.7 to 3.0 Ga	Pedra Branca	Troia Unit of the Cruzeta Complex		Brazil	2009	Inferred resource	6,600,000	0.23	0.03					2.27	2.27	Anglo Platinum (2009)

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Table 3. Tonnage and grade characteristics of contact-type copper-nickel platinum-group elements deposits. Values represent the total of resources and past production. Large igneous province (LIP) names and ratings from Ernst and Buchan (2001).

Magmatic event	LIP Rating	Approximate age (Ma)	Deposit name	Property name	Intrusion1	Intrusion2	Country	Aggregrated	Area_sqkm	Depth of resource estimate, meters	Mine_type	Tons of ore	Ni, percent	Cu, percent	Pt, g/t	Pd, g/t	Au, g/t	Reference
Northern Baltica-1 (C) LIP events	A (1v)	2440	Ahmavaara	Suhanko project	Portimo	Suhanko Intrusion	Finland	one	0.8682	250	op	106,693,000	0.09	0.23	0.245	1.165	0.139	Puritch and others (2007)
Bushveld (C) LIP event	A (1s)	2054	Akanani	Akanani	Bushveld	Bushveld Complex, Potgietersrus Limb	RSA	one	3.8351	2000	ug	269,700,000	0.21	0.12	1.440	1.710	0.200	Lonmin Platinum (2007)
Bushveld (C) LIP event	A (1s)	2054	Aurora (Kransplaats, Nonnenwerth, LaPucella, and Altona)	Aurora Project	Bushveld	Bushveld Complex, Potgietersrus Limb	RSA	many	8.6364	200	op	133,430,000	0.05	0.08	0.436	0.714	0.191	Pan Palladium Limited (2005, 2007)
Stillwater (C) LIP event	B (4i)	2701	Benbow	Benbow	Stillwater	Stillwater Complex	USA	one	0.26603	457	op	130,065,264	0.22	0.22	0.007	0.011		Zientek (1993)
Keweenawan (C) LIP event	A (1v)	1099	Birch Lake	Birch Lake	Duluth	South Kawishiswi Intrusion	USA	one	2.5445	840	op	195,504,000	0.16	0.53	0.255	0.552	0.123	Routledge (2008)
Stillwater (C) LIP event	B (4i)	2701	Camp deposit	AMAX Camp deposit	Stillwater	Stillwater Complex	USA	one	0.090011		op	5,850,000	0.42	0.23	0.018	0.1385		Zientek (1993)
Northern Baltica-1 (C) LIP events	A (1v)	2440	Fedorovo	Fedorovo project	Fedorovo	Fedorovo Intrusion	Russia	one	2.0469		op	166,210,000	0.09	0.15	0.311	0.933	0.084	Barrick (2008); Schissel and others (2002); Mitrofannov and others (2007)
Keweenawan (C) LIP event	A (1v)	1100	Geordie Lake	Geordie Lake	Coldwell	Coldwell Complex	Canada	one	0.3940	200	op	29,800,000	0.01	0.33	0.030	0.550	0.040	P&E Mining Consultants, Inc. (2007)
Bushveld (C) LIP event	A (1s)	2054	Grass Valley, North and South Zones	Grass Valley Project	Bushveld	Bushveld Complex, Potgietersrus Limb	RSA	many	0.8475	160	op	93,507,000	0.11	0.03	0.510	0.590	0.030	Pan Palladium Limited (2008)
Northern Baltica-1 (C) LIP events	A (1v)	2440	Haukiaho	Haukiaho	Koilismaa	Koilismaa Layered Igneous Complex	Finland	one	0.4070	150	op	27,000,000	0.24	0.36	0.209	0.549	0.216	Iljina and others (2005)
Northern Baltica-1 (C) LIP events	A (1v)	2440	Konttijärvi	Suhanko project	Portimo	Konttijärvi Intrusion	Finland	one	0.3955	200	op	42,110,000	0.06	0.13	0.408	1.436	0.106	Puritch and others (2007)
Northern Baltica-1 (C) LIP events	A (1v)	2440	Lavotta	Lavotta	Koilismaa	Koilismaa Layered Igneous Complex	Finland	one		100	op	3,000,000	0.21	0.26	0.180	0.260	0.200	Matilla and others (1976); Lahtinen (1983)
Keweenawan (C) LIP event	A (1v)	1100	Marathon	Marathon PGM-Cu Project	Coldwell	Coldwell Complex	Canada	one	0.5924	350	op	70,200,000	0.03	0.32	0.250	0.910	0.090	P&E Mining Consultants, Inc. (2007)
Keweenawan (C) LIP event	A (1v)	1099	Maturi and Nokomis	Maturi and Nokomis	Duluth	South Kawishiswi Intrusion	USA	many	3.6948	900	op,ug	623,013,000	0.21	0.62	0.131	0.306	0.070	Clow and others (2006); Routledge (2007)
Keweenawan (C) LIP event	A (1v)	1099	Mesaba	Minnamax, Babbitt, AMAX area	Duluth	Partridge River intrusion	USA	one	9.1100		op	1,200,000,000	0.09	0.43				Vance (2007)
Bushveld (C) LIP event	A (1s)	2054	Mokopane	Mokopane	Bushveld	Bushveld Complex, Potgietersrus Limb	RSA	one	0.5778	320	op	39,740,000	0.15	0.09	0.220	0.330		Directorate of Mineral Resources (2006); AIM Resources (2005)
Stillwater (C) LIP event	B (4i)	2701	Mouat	Mouat	Stillwater	Stillwater Complex	USA	one	0.4931	580	op	132,000,000	0.31	0.29	0.004	0.011		Zientek (1993)
Northern Baltica-1 (C) LIP events	A (1v)	2440	Mt. General'skaya	Mt. General'skaya	Mt. General'skaya	Mt. General'skaya	Russia	one			op	53,333,000	0.51	0.26	0.225	2.025	0.008	Geological Survey of Finland (2009a)
Northern Baltica-1 (C) LIP events	A (1v)	2440	Niittylampi	Niittylampi	Portimo	Suhanko Intrusion	Finland	one		200	op	850,000	0.67	0.49	0.270	0.680	0.030	Lahtinen (1987)
Keweenawan (C) LIP event	A (1v)	1099	Northmet	Dunka Road, USS Dunka Road/area	Duluth	Partridge River intrusion	USA	one	1.8260	1040	op	492,300,000	0.08	0.27	0.065	0.237	0.034	Hunter (2006)
Tertiary slab window		40	Nunatak-Brady Glacier	Nunatak-Brady Glacier	La Perouse	La Perouse - Crillon	USA	one	1.265264	600		90,000,000	0.53	0.33	0.116	0.113		U.S. Bureau of Mines (1991); Czamanske and others (1981); Himmelberg and Loney (1981)
Stillwater (C) LIP event	B (4i)	2701	Nye Basin	Nye Basin	Stillwater	Stillwater Complex	USA	one	0.39076	457	op	284,783,688	0.22	0.254	0.003	0.009		Zientek (1993)
Bushveld (C) LIP event	A (1s)	2054	PPRust North and Boikgantsho JV (Drenthe, Overysel North, and PPRust North)	PPRust North and Boikgantsho JV	Bushveld	Bushveld Complex, Potgietersrus Limb	RSA	many	5.1630	500	op	1,667,914,500	0.11	0.15	0.775	0.903	0.124	Tulp and others (2005); Anglo Platinum (2006)
Matachewan (C) LIP event(s)	A (3)	2440	River Valley - Dana and Lismer (Dana North, Dana South, Lismer North, Lismer's Ridge)	Dana North, Dana South, Lismer North, Lismer's Ridge	River Valley	River Valley Mafic intrusion	Canada	many	0.6563	300	op	28,168,000	0.02	0.10	0.332	0.968	0.060	Pacific North West Capital Corp. (2006)
Matachewan (C) LIP event(s)	A (3)	2440	River Valley - Varley	Varley	River Valley	River Valley Mafic intrusion	Canada	one	0.2865	150	op	4,803,000	0.02	0.07	0.341	0.936	0.057	Pacific North West Capital Corp. (2006)
Stillwater (C) LIP event	B (4i)	2701	Rocky Claim Group (Chrome Lake)	Rocky Claim Group	Stillwater	Stillwater Complex	USA	one	0.122937	213	op	49,000,000	0.28	0.26	0.005	0.011		Zientek (1993)
Bushveld (C) LIP event	A (1s)	2054	Rooiport, M2 and L3 zones	Rooipoort	Bushveld	Bushveld Complex, Potgietersrus Limb	RSA	one	3.9358	200	op	18,128,000	0.19	0.11	0.470	0.736	0.085	Verbeek and Lomber (2005)
Northern Baltica-1 (C) LIP events	A (1v)	2440	Rusamo	Rusamo	Koilismaa	Koilismaa Layered Igneous Complex	Finland	one		100	op	1,500,000	0.24	0.39	0.266	0.384	0.150	Lahtinen (1983)
Bushveld (C) LIP event	A (1s)	2054	Sandsloot	PPRust: Potgietersrust Platinums Limited	Bushveld	Bushveld Complex, Potgietersrus Limb	RSA	one	1.0309	500	op	320,160,000	0.09	0.17	1.163	1.348	0.208	Anglo Platinum (2006)
Keweenawan (C) LIP event	A (1v)	1099	Serpentine	Serpentine (Bear Creek/AMAX)	Duluth	South Kawishiswi Intrusion	USA	one	0.8343		op	6,350,400	0.30	0.88				Miller and others (2002)
Bushveld (C) LIP event	A (1s)	2054	Sheba's Ridge	Sheba's Ridge	Bushveld	Bushveld Complex, eastern limb	RSA	one	5.0390	400	op	716,000,000	0.19	0.07	0.210	0.620	0.080	Ridge Mining plc (2008)
Keweenawan (C) LIP event	A (1v)	1099	Spruce Road	Spruce Road (INCO)	Duluth	South Kawishiswi Intrusion	USA	one	1.7138	530	op	405,100,000	0.14	0.38				Routledge and Cox (2007)
Northern Baltica-1 (C) LIP events	A (1v)	2440	Suhanko	Suhanko	Portimo	Suhanko Intrusion	Finland	one		100	op	1,000,000	0.27	0.31	0.200	0.900	0.030	Geological Survey of Finland (2009b)
Northern Baltica-1 (C) LIP events	A (1v)	2440	Vaaralampi	Vaaralampi	Portimo	Suhanko Intrusion	Finland	one		150	op	6,050,000	0.31	0.20	0.200	0.550	0.060	Geological Survey of Finland (2009c); Reino and others (1978)
Bushveld (C) LIP event	A (1s)	2054	War Springs	War Springs	Bushveld	Bushveld Complex, Potgietersrus Limb	RSA	one	1.4739	500	op	46,965,000	0.13	0.10	0.250	0.780	0.070	Platinum Group Metals (2008)
Keweenawan (C) LIP event	A (1v)	1099	Wetlegs	Wetlegs (Bear Creek/Exxon)	Duluth	Partridge River intrusion	USA	one	1.3243		op	34,473,600	0.10	0.29				Miller and others (2002)
Bushveld (C) LIP event	A (1s)	2054	Zwartfontein South	PPRust: Potgietersrust Platinums Limited	Bushveld	Bushveld Complex, Potgietersrus Limb	RSA	one	0.2597	300	op	145,720,000	0.10	0.19	1.055	1.156	0.166	Anglo Platinum (2006)

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Table 4. Ages of intrusions that host reef-type platinum-group elements and contact-type Cu-Ni-PGE deposits.

[LIP (large igneous province) event names from Ersnt and Buchan (2001); La Perouse data by K-Ar and Ar-Ar; Penikat data by Sm-Nd; all others by U-Pb dating of zircon; PGE, platinum-group elements; Ma, million years]

Intrusion	LIP event	Age (Ma)	Reference	Mineral deposits
La Perouse		19.3±0.7 to 41.1±2.2	Hudson and Plafker (1981); Loney and Himmelberg (1983)	Contact-type deposits
Skaergaard Intrusion	NAVP (North Atlantic Volcanic Province)	55.59±0.13	Hamilton and Brooks (2004)	Reef-type PGE
Duluth Complex (Partridge River Intrusion)	Keweenawan	1095.94±0.18	Hoaglund (2010)	Contact-type deposits
Coldwell Complex	Keweenawan	1108±1	Heaman and Mackado (1992)	Contact-type deposits
Panton Sill	East Kimberley	1856±2	Page and Hoatson (2000)	Reef-type PGE
Bushveld Complex	Bushveld	2054.4±1.3	Scoates and Friedman (2008)	Reef-type PGE; contact-type deposits
Penikat Intrusion	Northern Baltica-1	2410±64	Huhma and others (1990)	Reef-type PGE
Mount General'skaya Intrusion	Northern Baltica-1	2496±10; 2446±10	Bayanova and others (2009)	Contact-type deposit
Federova-Pana Intrusion	Northern Baltica-1	25326±6; 2496±7	Nitkina (2006)	Reef-type PGE; contact-type deposits
Portimo Complex (Suhanko-Konttijärvi and Narkaus Intrusions)	Northern Baltica-1	2440 to 2435	Iljina (1994)	Reef-type PGE; contact-type deposits
River Valley Intrusion	Matachewan	2475 +2 -1	James and others (2002)	Contact-type deposits
Great Dyke	Great Dyke of Zimbabwe	2575.4±0.7	Oberthür and others (2002)	Reef-type PGE
Stillwater Complex	Stillwater	2704±4	Premo and others (1990)	Reef-type PGE; contact-type deposits
Troia Unit of the Cruzeta Complex		2.7 to 3.0 Ga	Fetter (1999)	Reef-type PGE
Munni Munni Intrusion	West Pilbara	2935±16	Arndt and others (1991)	Reef-type PGE
Stella Intrusion		3033.5±0.3	Maier and others (2003)	Reef-type PGE

Table 5. Examples of cut-off criteria used to define contact-type Cu-Ni-platinum-group elements deposits.

[PGE, platinum-group elements; GMV is gross metal value; NMV is net metal value; NSR is net smelter return]

Intrusion	Deposits	Cut-off criteria
Portimo Complex, Finland	Suhanko and Kontijärvi	0.8 g/t Pt+Pd+Au
Koilismaa Intrusion, Finland	Lavotta and Niittylampi	0.7% (Cu + 2xNi)
River Valley Intrusion, Ontario	Dana, Lismer, Varley	0.7 g/t Pt+Pd
Bushveld, Platreef, South Africa	War Springs Boikgantsho JV Rooipoort	Pt+Pd+Rh = 300 cmg/t US$10 GMV/t 0.5 g/t PGE+Au
Duluth Complex, Minnesota	Spruce Road Serpentine Northmet Maturi and Nokomis	0.26% copper equivalent 0.6% Cu US$7.42 NMV/t US$25 NSR and 0.8% Cu
Stillwater Complex, Montana	Mouat	0.1% Ni and 0.1% Cu

Table 6. Summary statistics of contact-type Cu-Ni-platinum-group elements deposits reported in table 2.

[PGE, platinum-group elements; g/t; grams per ton]

	Tons of ore	Ni, percent	Cu, percent	Pt, g/t	Pd, g/t	Au, g/t
Minimum	850,000	0.01	0.03	0.0032	0.0087	0.0080
Quantile–25th	22,564,000	0.09	0.13	0.1234	0.2832	0.0529
Median	70,200,000	0.16	0.25	0.2450	0.6200	0.0846
Quantile–75th	232,602,000	0.26	0.33	0.3746	0.9346	0.1539
Maximum	1,667,914,500	0.67	0.88	1.4400	2.0250	0.2160
Mean	206,497,877	0.19	0.26	0.3212	0.6825	0.1019
Number of deposits	37	37	37	33	33	26