Exploration strategies for Precambrian layered mafic–ultramafic intrusions in the East Kimberley

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The Palaeoproterozoic layered mafic–ultramafic intrusions in the Halls Creek Orogen (HCO) of the East Kimberley, Western Australia, represent one of the most extensively mineralised igneous associations of their type in Australia. The intrusions contain a range of magmatic and hydrothermal deposits of platinum-group elements (PGEs), chromium, nickel, copper, cobalt, titanium, vanadium, iron and gold. Despite intensive exploration during the past four decades and the discovery of many prospects, none of the deposits associated with the layered intrusions has proved to be economic.

AGSO and the Geological Survey of Western Australia, as part of the National Geoscience Mapping Accord Kimberley–Arunta project, have extended the distribution of prospective layered intrusions and highlighted the potential for different styles of mineralisation with prominent surface expressions and remote sensing–geophysical signatures.

Major findings relating to the intrusions are summarised in the following *AGSO Research Newsletter* articles: geology,[1, 2] mineralisation,[3–6] geochronology,[7] depths of emplacement,[8] and also the soon-to-be-released AGSO Bulletin 246. (See contents list on page 12.)

Geological setting and classification

The layered intrusions are restricted to the central and western zones of the HCO—a well-exposed north-north-east trending (~400 km long by 120 km wide) orogenic belt. The belt comprises variably deformed and metamorphosed sedimentary, volcanic, and intrusive Palaeoproterozoic rocks, and overlapping Proterozoic and Palaeozoic basinal sequences. The intrusions have been assigned to seven major groups (I–VII) on the basis of rock types, U–Pb geochronology, contact relations with country rocks, metamorphic–structural history, types of mineralisation, trace-element chemistry, and Sm–Nd isotopic composition. They form folded sheets, shallow-dipping basinal bodies, composite multi-chambered bodies, funnel-shaped bodies, steeply plunging plugs, fault-bounded blocks, narrow dyke-like bodies, and screens between granite plutons. Chilled and contaminated margins, contact aureoles, ribbon-like comagmatic satellite intrusions, net-vein complexes (resulting from mingling of mafic and felsic magmas), and feeder conduits indicate that the intrusions crystallised in situ, rather than being tectonically emplaced blocks that crystallised elsewhere.[1]

Most intrusions were derived from olivine tholeiite and quartz tholeiite parent magmas of basaltic affinity (with mg number = 100 x Mg/(Mg+Fe^{2+}) = 67 or less). Incompatible trace-element abundances are consistent with compositions ranging from mid-ocean ridge basalt to continental tholeiite.[9] High average S contents (520–1570 ppm) in cumulate rocks for most groups of intrusions indicate early S saturation for the parent magmas. The intrusions were emplaced into the crust at depths ranging from approximately eight to 23 kilometres (2.4–6.7 kb) and there were at least three major periods of emplacement (1855 Ma, 1845 Ma and 1830 Ma). Emplacement of the 1855 million-year intrusions (groups I–III) was contemporaneous with granite plutonism (part of the Bow River Batholith) and felsic volcanism (Whitewater Volcanics) during a major magmatic event that represented a large flux of heat into the crust. Most of the layered intrusions can be classified as late orogenic to postorogenic bodies emplaced during more quiescent phases between periods of active tectonism in a complex orogenic belt.

Mineralisation

Mineral deposits hosted by the layered intrusions can be broadly classified into three major orthomagmatic associations (chromite, sulphide, and Fe–Ti oxide) reflecting an apparent secular evolution of mineralising systems (i.e. Cr–PGEs→Ni–Cu–Co–PGEs→Fe–Ti–V). A fourth association relates to hydrothermal polymetallic deposits.

Chromite association (Cr–PGEs–Ni–Cu±Au)

Chromite is a ubiquitous cumulus mineral in the 1855 million-year, group I mafic–ultramafic intrusions (Panton, Big Ben, West Panton, Highway, Melon Patch, South Melon Patch, West McIntosh, Mini, West Robin Soak*) and in some coeval group II mafic intrusions (e.g. Springvale and Wilagee). In group I, chromite is associated with cumulus olivine in cyclic units of dunite, peridotite and harzburgite. In group II, it occurs with plagioclase in troctolite, anorthosite and leucogabbro. Of greatest economic significance are stratabound chromitite layers at similar stratigraphic levels in the upper parts of the ultramafic stratigraphy of group I intrusions (figure 1). In the Panton intrusion, these chromitites (Middle Group) extend for up to 12 kilometres along strike and are enriched in Pt (up to 2850 ppb), Pd (2470 ppb) and Au (153 ppb) relative to the chromitites from other stratigraphic levels in the intrusion. The chromitites range from single massive isomodal layers up to 2.4 metres thick, to very thin grain-size laminations, stacked cyclic packages of alternating chromitite and dunite layers, and thin discontinuous

* Locations of all intrusions are shown in figure 10 of Trudu & Hoatson 1996.

stringers and lenses. Average Pt+Pd abundances of chromitites for the East Kimberley intrusions decrease from: Panton (Middle Group), Big Ben, Panton (Lower Group), South Melon Patch, West McIntosh, Panton (Upper Group), West Panton, Mini, to Wilagee. This order generally correlates with decreasing thickness of the ultramafic component in the intrusion, implying that the PGE abundances of the chromitites are related to the volume of the ultramafic magma.

The PGE-enriched chromitites generally occur from two to 150 metres below the contact of the ultramafic and overlying mafic zones. There is a correlation between the thickness of these chromitite layers and the thickness of the ultramafic sequence. The thickest layers are in the Panton and Big Ben intrusions, which contain the thickest sequences of olivine bearing cumulates—650 and 1700 metres respectively. PGE-poor chromitite layers are also developed in the lower parts of these thicker bodies. There also appears to be a relationship between the stratigraphic level of the PGE-enriched chromitites and the relative thickness of the ultramafic sequence. For example, the distance of the most PGE-rich chromitite layer below the mafic–ultramafic contact generally increases progressively with increasing thickness of the ultramafic sequence.

Sulphide association (Ni–Cu–Co±PGEs)

Sub-economic concentrations of Ni–Cu–Co±PGE sulphides are hosted by the 1845 million-year group V mafic–ultramafic intrusions (Corkwood, Dave Hill, Fletcher Creek, Keller Creek, McKenzie Spring, Sally Malay, Spring Creek, and Wilson Creek—see figure 1). Massive sulphides generally occur in fractionated gabbroic and noritic rocks, which form basal units five to 40 metres thick, between the overlying peridotite and the paramigmatite footwall rocks. Matrix and disseminated sulphides persist into the overlying peridotite and gabbroic rocks (olivine gabbro, troctolite, leucogabbro, anorthosite). Indicated resources are typically one to four million tonnes @ 1–2% Ni+Cu, ~0.1% Co, ~0.5 ppm total PGEs. There is also significant sulphide mineralisation in mafic granulite bodies of the Tickalara Metamorphics (e.g. Norton and ?Bow River), but these deposits have lower Ni/Cu ratios (0.5:1 to 2:1) than those hosted by the group V intrusions (2:1 to 5:1).

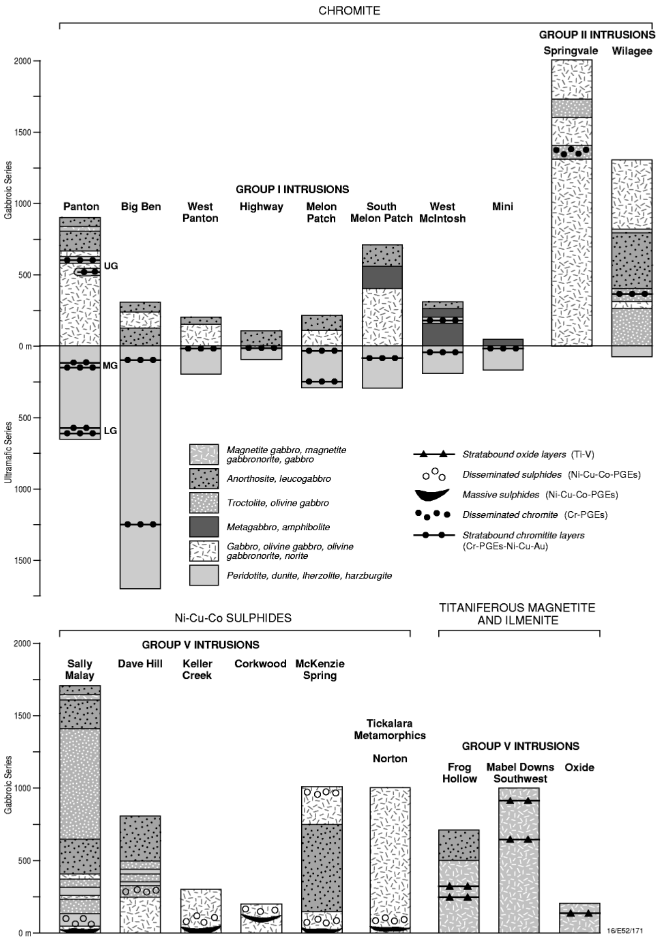

Figure 1. Stratigraphic distribution of chromite, Ni–Cu–Co sulphides, and titaniferous magnetite and ilmenite in the East Kimberley layered mafic–ultramafic intrusions. The vertical axis shows the thicknesses of the Ultramafic Series and Gabbroic Series for each intrusion. Chromitites in the Panton intrusion are shown as Upper Group (UG), Middle Group (MG) and Lower Group (LG).

Sulphide textures in the group V intrusions generally show little evidence of strain or recrystallisation. Those in the granulite bodies, however, consist of discontinuous massive recrystallised bands and thin lenticular segregations subparallel to the foliation of the host metagabbros.

Massive sulphides show a clear association with the lower parts of the stratigraphy—along, or very near, the basal contact of the intrusion or in the feeder conduit. The geometry of the basal contact and conduit is important because the massive sulphides need to be concentrated in restricted environments if economic grades are to be attained. Massive sulphides in the Sally Malay intrusion are concentrated in a keel-shaped depression of an interpreted feeder conduit.[6] In the McKenzie Spring intrusion they occur in a 1600-metre-long, fault-controlled structural embayment that is transgressive to the footwall country rocks. Accumulation of these sulphides is also greatest below the thickest part of the overlying cumulates. The widespread (and thinness of) mineralisation in the Norton and Bow River granulite intrusions indicates that there may not have been a suitable basal depression for concentrating dense sulphides by gravitational processes.

Significantly, the major footwall rocks for all mineralised group V and mafic granulite intrusions are high-grade metasediments (generally garnet–cordierite–sillimanite–spinel–biotite–feldspar–quartz paragneisses) of the Tickalara Metamorphics. The siliceous character and, presumably, ease of assimilation of these rocks make them favourable country rocks for changing the sulphide solubility of the mafic magmas—an important requirement for the precipitation of sulphides.

Fe–Ti oxide association (Fe–Ti–V)

Concentrations of titaniferous magnetite and ilmenite are hosted by gabbroic rocks in the middle to upper fractionated parts of the 1845 million-year group V (Frog Hollow, Mabel Downs Southwest, Ord Crossing, Oxide) and 1830 million-year group VI (McIntosh) mafic intrusions (figure 1). Their distribution highlights the evolved and tholeiitic character of the intrusions. Their association with the younger intrusions is consistent with the general progression from early, more primitive mineralising magmatic systems to later, more evolved systems in the HCO.

Most Fe–Ti–V deposits appear to be small and have little potential for a large-tonnage resource. The Fe–Ti oxides are disseminated or form stacked sequences of thin (0.5–5 cm) cyclic units, thin discontinuous irregular layers, and thicker massive lenses. The Frog Hollow mafic intrusion contains a number of massive oxide lenses (up to 39.4% TiO_2, 0.99% V, 60.6% total Fe as Fe_2O_3, and 0.93% Cr) hosted by ferrogabbro and leucogabbro.[5] The lenses form small, prominent hills, five to 15 metres high, incised by creeks containing abundant oxide alluvium. The coarse grain-size of the Fe–Ti oxides and high TiO_2 grades may reflect high-temperature subsolidus annealing and grain enlargement processes related to later metamorphism. Fe–Ti oxides in the large McIntosh intrusion form disseminations (up to 10 vol %) in troctolite, olivine gabbro and gabbronorite, and thin cyclic units (up to 50 vol %) in leucogabbroic rocks in the upper half of the intrusion.

Hydrothermal polymetallic association (Pd, Pt, Cu, Zn, Pb, Au)

Hydrothermal remobilised polymetallic deposits historically have not been a priority target for exploration in the HCO. However, this province contains many favourable ore-forming components (e.g. fluids, structural conduits, heat and metals) for such deposits. Indicators include widespread serpentinisation of ultramafic sequences, reactivated faults that cut rocks of different composition, multiple phases of metamorphism and deformation, high crustal heat flux from coeval gabbroic and granitic intrusions, and high regional background concentrations of PGEs.

The Emull Zn–Cu–Pb–Ag prospect is an example of hydrothermal remobilised mineralisation spatially associated with a mafic intrusion.[10] This polymetallic prospect (demonstrated resource of 4.7 Mt @ 4.5% Zn, 0.33% Cu, 0.2% Pb, and 19 ppm Ag) occurs near the contact between the differentiated Emull Gabbro and poorly exposed lateritised metasediments of the Koongie Park Formation. The mineralisation consists of a series of en echelon lenses and pods of disseminated and massive sulphides comprising sphalerite–galena–chalcopyrite–pyrite–pyrrhotite in ‘serpentinite’ and a diopside–carbonate–chlorite calc–silicate rock interpreted by Griffin et al. to be assimilated and metasomatised country rock in the gabbro.[10]

The coeval relationships of many mafic and felsic magmatic systems in the HCO highlights the potential for the secondary redistribution of base and precious metals by volatiles or volatile-enriched magmas (e.g. breccia-type and constitutional zone refining mineralisation described by Barrie[11]). Investigations for these deposits should focus on zones of alteration, hybridisation and brecciation near the contacts of coeval granite and gabbro bodies. Since serpentinisation alteration is an efficient mechanism for concentrating PGEs, thick sequences of serpentinised and faulted olivine-rich cumulates should also be targeted.

Exploration strategies

Some of the more important considerations when exploring for PGE-enriched chromitite layers and basal segregations of sulphides in the HCO are listed below.

Stratabound PGE-enriched chromitite layers

Group 1 differentiated intrusions (figure 2a) in the central zone that display open fractionation systems with repeated large pulses of primitive magma into the chamber (Panton, Big Ben, West McIntosh, Melon Patch group) are thought to be the most prospective. Intrusions formed from the most primitive magmas (mg >58, corresponding to olivine compositions with mg >82) and which contain thick sequences of olivine cumulates should be high priority.

The most PGE-enriched chromitites generally occur in the stratigraphic interval two to 150 metres below the contact of the Ultramafic and Gabbroic Series.

Detailed geological mapping and closely spaced sampling (initially 10–20 m spacing) are needed to determine magma-chamber processes that are important for the formation of chromitite layers, such as the mixing of primitive magma with more fractionated magma. Magma mixing can be indicated by:

- rapid changes in the composition of cumulus minerals and the volume of intercumulus melt in the cumulates (rock porosity) across a layered sequence;
- development of porphyritic, pegmatoidal and orthocumulus textures in associated rocks;
- occurrence of hybrid rocks and accidental blocks in slump deposits;
- lateral variation of rock types, such as interfingering, thinning or thickening; and
- unconformities representing magmatic erosion/disruption of footwall sequences.

Olivine and/or orthopyroxene cumulates are more favourable than clinopyroxene cumulates for hosting stratabound chromitite layers because of the relative high partitioning of Cr into clinopyroxene.

Proximity of chromitite layers is indicated by the presence of disseminated chromite in associated ultramafic cumulates, blocks of chromite in soil, detrital chromite grains in stream sediments, and magnesite alteration of host ultramafic cumulates. Major geochemical pathfinder elements are Cr, Pt, Pd, Cu, Au, Mg, mg number, and Ni/Cu ratios.

Narrow thicknesses (most <0.5 m) and low primary magnetite and sulphide contents of the chromitite layers means electrical methods (e.g. electromagnetics, induced polarisation) have limited application (in contrast to basal Ni–Cu–Co sulphide deposits).

Aeromagnetics, gamma-ray spectrometry, and Landsat imagery (figure 2b) are useful for defining macroscopic features of intrusions, namely:

- aeromagnetics can help determine

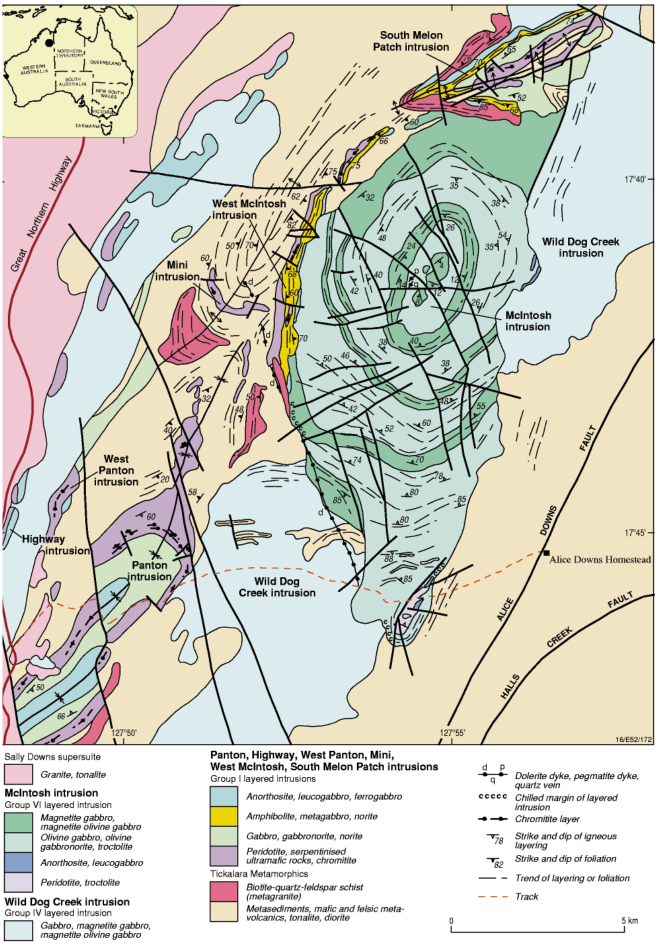

Figure 2a. Geological map of the group I (Panton, Highway, West Panton, Mini, West McIntosh, and South Melon Patch) mafic–ultramafic intrusions, group IV (Wild Dog Creek—part of) mafic intrusion, and group VI (McIntosh) mafic intrusion.

gross younging directions in gabbroic zones (coarse-grained primary Fe–Ti oxides) and the intensity of serpentinisation in ultramafic zones (fine-grained magnetite after olivine);

- composite gamma-ray spectrometry can define the regional distribution of mafic and ultramafic rocks, since these have low concentrations of K, Th and U; and
- Landsat 5 Thematic Mapper imagery, in particular, band-ratio (5/7, 5/3, 5: figure 2b) and directed principal component (2(4/3,5/7), 5/4, and 1+7) images are extremely useful for discriminating ultramafic, mafic and felsic rock types, and identifying favourable contacts between ultramafic and gabbroic sequences.

Basal segregations of Ni–Cu–Co±PGE sulphides

Differentiated layered mafic–ultramafic intrusions of group V (Sally Malay, Corkwood, Keller Creek, Wilson Creek, McKenzie Creek, etc.) and large massive mafic granulite bodies of the Tickalara Metamorphics (Norton) are considered the most prospective.

Establish whether the magma(s) that formed the intrusion were S saturated by determining:[12]

1. parent magma compositions (from chilled marginal rocks, comagmatic dykes and sills);
2. modal distribution of sulphides in cumulates and normalising S content of the intercumulus liquid (trapped melt) in unaltered cumulates to 100 per cent melt; or
3. S/Se ratios of unaltered cumulates. In general, most basaltic parent magmas with S content exceeding 1000 ppm are S saturated. If the intrusion is in part S undersaturated, the stratigraphic level of S saturation will need to be determined for stratabound PGE-enriched sulphide layers (cf. Munni Munni Complex-type in the west Pilbara Craton[12]).

Favourable country rocks are paramigmatites (Tickalara Metamorphics) and metasediments (Halls Creek Group), rather than metavolcanics or granites. Assimilation of metasediments containing S-bearing minerals (e.g. pyrrhotite, pyrite, gypsum, anhydrite) and graphite may induce the precipitation of sulphides in the contaminated magma.

Obtain evidence for crustal contamination of magma—for example:

- association of sulphides and alkali minerals;
- fractionated marginal rocks;
- abundance of accidental xenoliths and xenocrysts in the basal zones;
- mixed Sm–Nd and Re–Os isotopes;
- S-isotope compositions outside normal magmatic values;
- variable compatible versus incompatible elemental ratios in an intrusion; and
- different crystal fractionation trends in the same magmatic province.

Field investigations should carefully reconstruct the configuration of the basal contact, particularly below the thickest part of the mafic–ultramafic cumulates. Depressions and fault-controlled structural embayments are important for the accumulation of massive sulphides from gravitational and/or crustal contamination processes.

Feeder conduits to the intrusions are also favourable environments for the concentration of sulphides. The dynamics of the magma flow may be important for the deposition of massive sulphides; for example, fluid dynamic contrasts (fast, slow, turbulent, passive) associated with the change from narrow vertical conduits to broad sub-horizontal open magma chambers.[13]

Remobilised discordant and

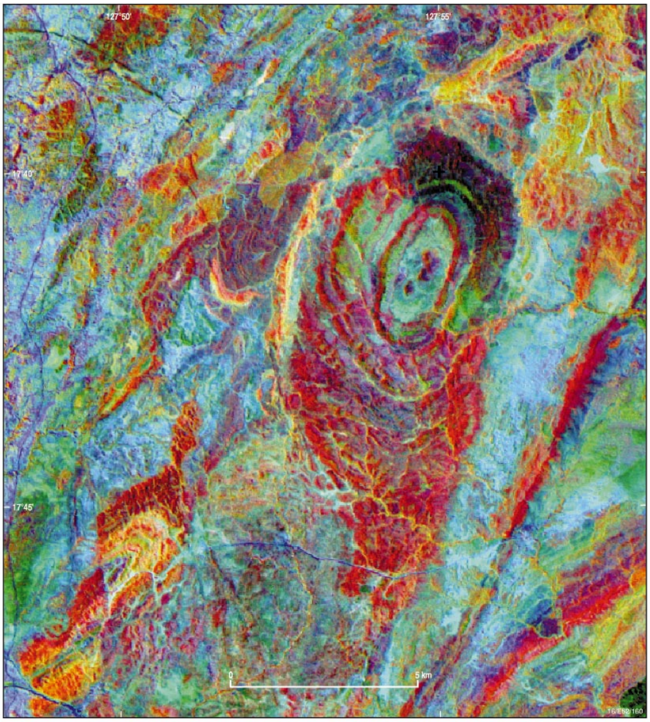

Figure 2b. Landsat-5 TM (path 107 row 72) colour composite 5/7 (to discriminate clays), 5/3 (iron oxides) and 5 (vegetation) image, displayed as red, green and blue, respectively, for the same area shown in Figure 2a. The image highlights the differentiated nature of the mineralised Panton and smaller group I intrusions further north, and the prospective contact region (for PGE-enriched chromitites) between the ultramafic cumulates and overlying gabbroic cumulates. The dark area in the north-east of the McIntosh intrusion is a fireburn. Image generated by LF Macias, AGSO.

fractionated ores enriched in Cu, Au, and/or Pd can occur far from the basal contact of the intrusion or in the country rocks.

Gossan search, stream sediment sampling, and rock geochemistry are recommended geochemical techniques. As well, electromagnetics, ground magnetics and induced polarisation are useful since most ore types contain pyrrhotite and magnetite. Aeromagnetics and gravity can delineate the regional extent, geometry and major structures of poorly exposed intrusions; gravity, subject to sufficient density contrast with the country rocks, can define feeder conduits.

Economic potential

The East Kimberley layered mafic–ultramafic intrusions are generally regarded as having greater potential for hosting an economic resource of Ni–Cu–Co sulphides rather than for PGEs associated with chromitite layers. Economic chromitite layers, such as those in the Great Dyke of Zimbabwe and the UG-2 in the Bushveld Complex of South Africa, typically have strike lengths of tens to hundreds of kilometres. They are hosted by large, layered bodies containing very thick sequences of olivine and orthopyroxene cumulates—none of which is typical of the East Kimberley intrusions. The economic viability of these deposits is usually dependent on the uniformity of PGE and Cr grades over long strike distances.

A major problem relating to the chromitite layers in the HCO is their variable morphology along strike. For example: the major chromitite layers in the Panton intrusion vary in thickness from a few centimetres to 240 centimetres over a few hundred metres along strike; are locally tightly folded; vary from a single massive layer to a package of several thin layers; and are displaced by high-angle cross-cutting faults. All these features potentially affect the lateral continuity of ore grades and hinder mining operations. In contrast, economic Ni–Cu–Co sulphide deposits are often hosted by small- to medium-sized mafic intrusions that may be layered or massive (common in the HCO). These types of deposits are also less dependent on the volume of magma and the dynamics of magma flow.

One of the major challenges in exploring for Ni–Cu–Co sulphide deposits in the HCO is to locate prospective intrusions that may be covered by shallow alluvium or underlie thick sequences of country rocks. The identification of two parallel north-east-trending metallogenic corridors containing the major mineralised intrusions (groups I, II and V) of the HCO will help focus exploration for these deposits.[8] Large prospective areas covered by shallow alluvium occur within these corridors and also in the southern parts of the HCO between Louisa Downs and Halls Creek. The identification of favourable basal contact and feeder conduit environments in these poorly exposed intrusions will most likely be achieved through advanced geophysical (airborne electromagnetic and gravity) and remote-sensing (e.g. ASTER—Advanced Spaceborne Thermal Emission and Reflection Radiometer) techniques in association with closely spaced grid drilling and, where possible, detailed mapping. Hoatson et al. have highlighted the potential of the East Kimberley and other Proterozoic provinces in Australia, such as the Musgrave Block in central Australia, for Ni–Cu–Co sulphide mineralisation associated with mafic–ultramafic intrusions.[6]

Other potential styles of mineralisation in the HCO that should be considered include:

- structurally controlled hydrothermal and constitutional zone refining mineralisation (such as Lac des Iles Intrusion, Ontario[11]);
- Ni–Cu–PGE sulphides in mafic sills related to flood basalts (such as Noril'sk-Talnakh, Russia[14]); and
- 'stratabound' Platinova Reef-type Au–PGE mineralisation (such as Skaergaard Intrusion, east Greenland[15]) related to ascending fluids in the upper parts of thick mafic intrusions.

Concluding statement

Exploration programs for Precambrian layered mafic–ultramafic intrusions vary considerably for different styles of precious and basemetal mineralisation. It is important not to be 'blinkered' by a particular model, but to maintain a flexible innovative approach and consider different styles of orthomagmatic and hydrothermal mineralisation at different stratigraphic levels in the intrusion.

It took more than 20 years of intensive exploration to define the J-M Reef of the Stillwater Complex, and it was not until late in the 1990s that a significant Au–PGE layer (Platinova Reef) was found in the Skaergaard Intrusion, east Greenland—an intrusion that had been investigated in great detail for more than 60 years.

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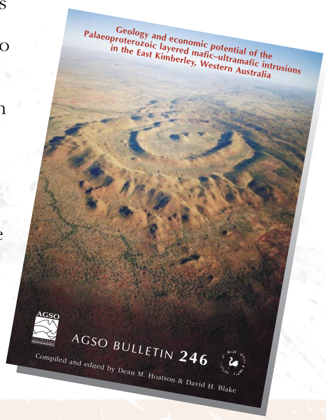

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