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MAFIC–ULTRAMAFIC INTRUSION-HOSTED NI–CU–PGE DEPOSITS: MINERAL SYSTEMS ATLAS EXPLANATORY NOTES

LL Grech and G da Silva

Department of Energy, Mines, Industry Regulation and Safety

GOVERNMENT OF WESTERN AUSTRALIA

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Cover image One of the largest and most distinctive metagranitic units in the Gascoyne Province, the Davy Well Granite emerges from the water of the Yinnetharra Pool along the Gascoyne River. Photo by Angela Riganti

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Mafic–ultramafic intrusion-hosted Ni–Cu–PGE deposits: Mineral Systems Atlas Explanatory Notes

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Abstract

Western Australia contains sizeable mafic–ultramafic intrusion-hosted Ni–Cu–PGE deposits including Nebo-Babel, Savannah, and Nova-Bollinger. A mineral systems analysis has been performed to define critical and constituent processes controlling their genesis, as well as mappable proxies for these processes. Critical processes include: i) formation of large volumes of mafic–ultramafic magmas that will feed the host intrusions; ii) lithospheric-scale structures that facilitate magma transport through the crust and the development of dynamic subvolcanic feeder systems; iii) sulfur saturation; iv) the sequestering of metals into sulfides; v) the concentration of metal-rich sulfides; and vi) modification, weathering, and preservation of the original ore body. The constructed Mineral System Tree for mafic–ultramafic intrusion-hosted Ni–Cu–PGE deposits demonstrates the link between geological processes and their recommended GIS map layers for exploration.

KEYWORDS: copper, intrusions, nickel, platinum group elements (PGE)

Introduction

The Mineral Systems Atlas (MSA) is an interactive GIS-based platform that collates and delivers map-based geoscience data layers specifically relevant to understanding and exploring mineral deposits in Western Australia at a regional scale. Accompanying the Atlas is the Guide, which provides more information on the approach used, and importantly, specific information on how the individual layers were created, thus complementing the metadata and data dictionary information. All data layers in the MSA are available for downloading from the Data and Software Centre using the links provided.

These Explanatory Notes aim to provide background information on the conceptual basis for the layers used in the MSA relevant to the mineral system under consideration, and to describe in detail the reasoning behind their selection and their limitations. Information in the Guide and Atlas is likely to evolve and be updated based upon improvements in our understanding of the mineral system, and when additions of related geoscience data become available.

Atlas content is systematically defined by applying the mineral systems concept (Wyborn et al., 1994; McCuaig et al., 2010); mineral deposits will only form and remain preserved where there has been a spatial and temporal coincidence of critical processes (geodynamic setting, lithosphere architecture, fluid–rock interaction, ligand and ore component reservoir/s, fluid flow drivers and pathways, depositional mechanisms, post-depositional processes). These critical processes might be recognized from mappable geological features (targeting elements or geological proxies) expected to result from them.

Mineral systems analysis is the term used to describe the process of identifying critical and constituent processes, geological proxies for these processes, and translating them into mappable proxies. The outcome of this work is summarized in a Mineral System Tree (Fig. 1). Such analyses draw upon existing literature, in-house knowledge, and collaborations with subject matter experts. Note that it is not unusual for geological proxies to represent more than one critical process – hence they can be listed multiple times in the Mineral System Tree and labelled accordingly in the MSA. Structured queries are then used to extract data relevant to those mappable proxies from one or more statewide databases. Where practical, queries are dynamically linked to primary Geological Survey of Western Australia (GSWA) geoscience data sources and are scheduled to update automatically so that new data are incorporated.

It is acknowledged that all datasets have their own limitations both with respect to their validity as proxies for the processes that they represent as well as with respect to their physical attributes such as sampling or interpretation bias and applicable scale. Also, the timing aspects of the proxies are not captured in many datasets, so further investigation is usually required to ascertain their significance in specific areas of interest. In general, the datasets used in the MSA are most relevant for use at the regional scale and hence are not suitable for detailed exploration targeting. With respect to the mafic–ultramafic intrusion-hosted Ni–Cu–PGE system in the MSA, most ‘field observations’ and ‘geochemistry’ data are sparse in the deeper sedimentary basins, such as the Perth, Canning, Carnarvon and Officer Basins. These are readily identified in the ‘Primary data layers’: ‘Tectonic units 1:500 000’ layer. This sampling bias is mainly due to historical focus on petroleum-related factors within these basins and to the sparsity of wells in some areas.

The MSA uses mineral system groups based upon a scheme proposed by Geoscience Australia (Fraser et al.,

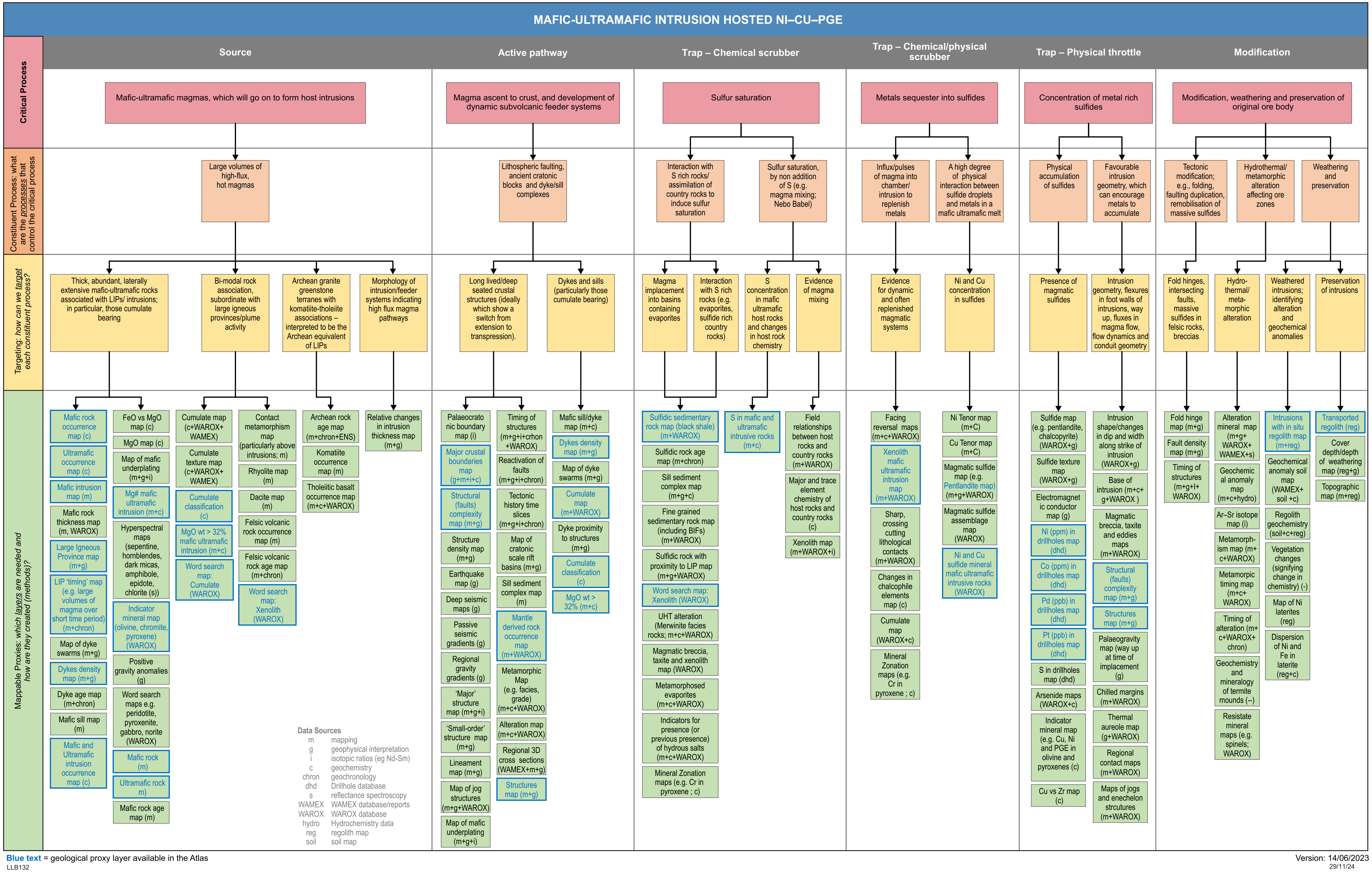

Figure 1. The Mineral System Tree is the graphical display of a mineral systems analysis – showing the link between critical/constituent processes and their recommended targeting features and GIS layers

2007). Under this scheme, the mafic–ultramafic intrusion-hosted Ni–Cu–PGE system belongs in the orthomagmatic grouping wherein ore components are extracted and transported by magmas and are concentrated within these by igneous processes. This Record focuses specifically on Ni-rich examples (±Cu and PGE) including intrusion-hosted deposits related to flood basalts such as Noril'sk and Duluth. Along with the komatiite-hosted Ni–Cu–PGE system, the mafic–ultramafic intrusion-hosted Ni–Cu–PGE system represents an important style of Ni-rich mineralization that is currently being mined in Western Australia. Mafic–ultramafic intrusions can host several other orthomagmatic mineralization types including Ti, V, Cr, Fe, Co and variably PGE-enriched examples – specifically the anorthosite-hosted Fe–Ti–V system, the Merensky Reef-type Ni–PGE system and the ophiolite-hosted Cr–Ni system of Fraser et al. (2007). From this list, the anorthosite-hosted Fe–Ti–V system is currently included in the MSA as 'layered intrusion-hosted vanadium' (Guilliamse, 2020).

Mafic–ultramafic intrusion-hosted Ni–Cu–PGE deposits are found worldwide and represent some of the world's largest nickel deposits (Hoatson et al., 2006). Globally, they include world-class examples such as Jinchuan (China), Pechenga (Russia) and Voisey's Bay (Canada). In Western Australia, notable examples include Julimar (Gonneville; 660Mt @ 0.63 g/t Pd, 0.14 g/t Pt, 0.02 g/t Au, 0.15% Ni, 0.083% Cu, and 0.015% Co), Savannah (14.57 Mt @ 1.49% Ni, 0.67% Cu and 0.10% Co), Nebo-Babel (West Musgrave; Nebo: 50 Mt @ 0.34% Ni and 0.32% Cu; Babel: 340 Mt @ 0.3% Ni and 0.33% Cu), and Nova-Bollinger (3.9 Mt @ 1.81% Ni, 0.70% Cu and 0.060% Co; current mineral resources estimates sourced from MINEDEX; Fig. 2).

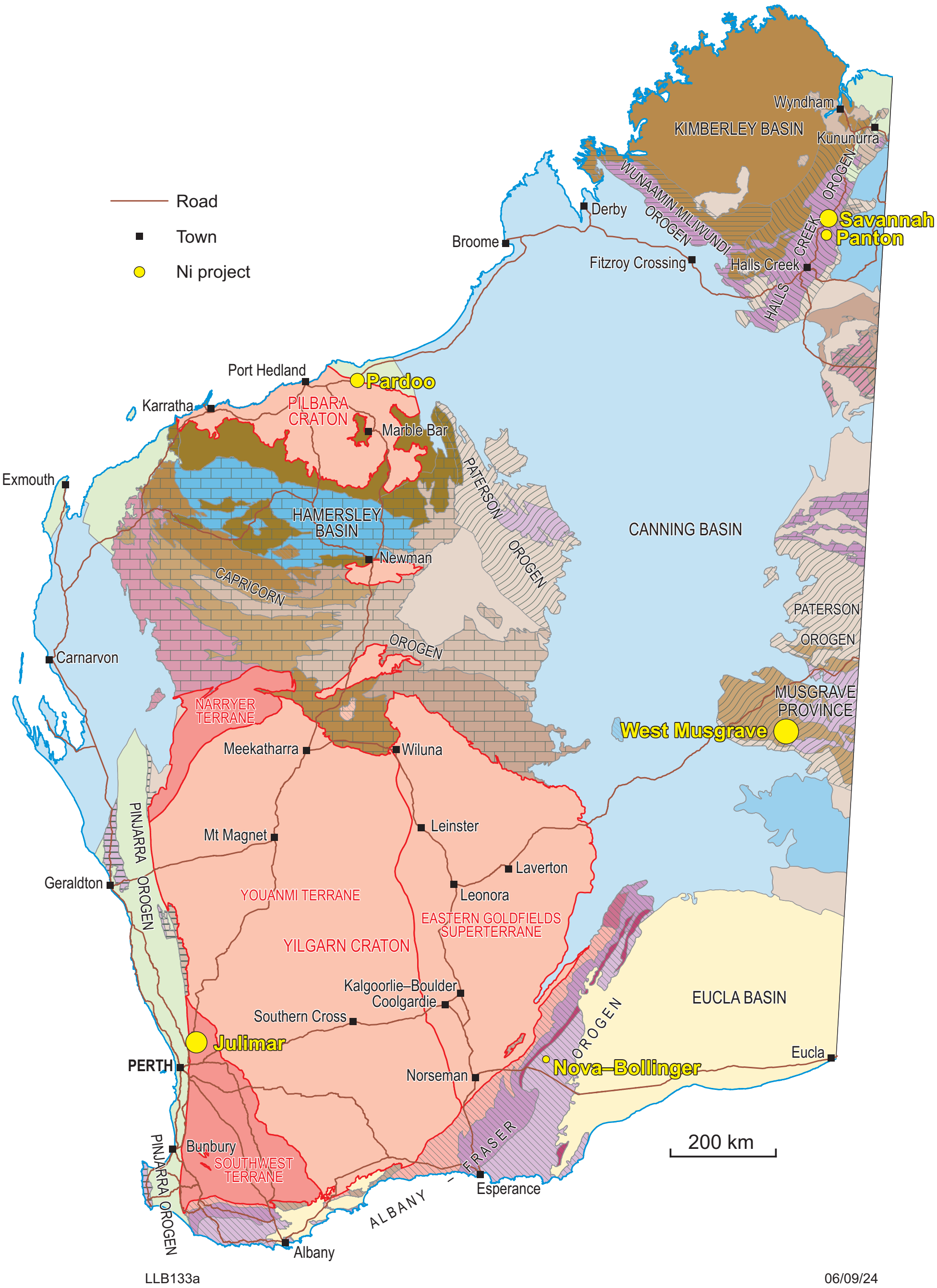

Figure 2. Mafic–ultramafic intrusion-hosted Ni (± Cu ± PGE) projects in Western Australia with >140 kt contained Ni in sulfides (plus Nova-Bollinger), sized proportional to kt amount. Overlain on 1:10 000 000 Simplified Tectonic Map of Western Australia (compiled 2022). Resources figures from MINEDEX database

The 'Mineralization localities' section in the MSA provides information on the locations of all current operating mines that have nickel as their main product as well as mineralization sites for each of the constituent commodities. As mineralization sites vary greatly in their economic significance, where possible they are classified accordingly. Note that only a small subset of these mineralization localities relates directly to mafic–ultramafic intrusion-hosted Ni–Cu–PGE mineralization. These are shown as 'Mafic and ultramafic – layered mafic intrusions' within the 'Mineralization style – Nickel' layer. Some localities identified as 'Mafic and ultramafic – undivided' may also be relevant to this system.

Overall, the metallogenesis of mafic–ultramafic intrusion-hosted Ni–Cu–PGE mineralization is well understood. This mineral systems analysis is informed by key existing literature (Schulz et al., 2014; Barnes et al., 2016; Barnes, 2023), and additional consultation with subject matter experts and industry representatives. Results of the mineral systems analysis are presented in graphic form as a Mineral System Tree (Fig. 1), which formed the basis for the selection of the mappable proxies used in the MSA.

Characteristics of mafic–ultramafic intrusion-hosted Ni–Cu–PGE systems

Although no single intrusion shape appears to significantly favour mineralization (Barnes et al., 2016; Fig. 3), Barnes and Mungall (2018) note that intrusions associated with Ni–Cu–PGE mineralization tend to have horizontal (or subhorizontal) rather than vertical extents. Consequently, chonoliths and elongate sills present attractive exploration targets (e.g. Noril'sk and Nebo-Babel; Fig 3; Barnes et al., 2016). Barnes and Mungall (2018) further suggest that blade-shaped dykes, while apparently having limited mineralization potential, may represent an end-member of intrusion geometry. These shapes could progressively evolve into more prospective forms, such as tube-funnel transitions and potentially tubular chonoliths, during emplacement. This evolution might occur through processes such as:

> lateral propagation of dikes, widening of conduits due to preferential thermal erosion of country rocks, gravity flow of sulfide–silicate–xenolith slurries, and self-enhancing propagation of sulfide vein-dike networks into process zones in country rocks—coupled with post emplacement tilting and random intersection with present-day erosion surfaces (Barnes and Mungall, 2018).

The critical processes required for mafic–ultramafic intrusion-hosted Ni–Cu–PGE deposits, discussed below, closely resemble those identified for komatiite-hosted Ni–Cu–PGE deposits (e.g. Grech, 2022), and are summarized in Barnes et al. (2016). Key differences between these two deposit types are outlined in Table 1. These include: i) komatiite-hosted deposits are mostly Archean in age, while intrusion-hosted deposits span much of Earth's history (140–2892 Ma; Hoatson et al., 2006); and ii) intrusion-hosted deposits can be associated with rocks derived from magmas with mafic or ultramafic bulk compositions (Barnes et al., 2016), whereas komatiite-hosted deposits are exclusively linked to magmas of ultramafic bulk composition.

A requirement common to both systems is the presence of high-flux magma pathways, which are a critical factor in both the source and trap components of these mineral systems (Barnes et al., 2016). These pathways are commonly represented by cumulate rocks and offer several advantages: they promote the assimilation of wall rocks, leading to the addition of external sulfur; they facilitate interaction between large volumes of magma and sulfide droplets, resulting in higher ore tenors; and they concentrate large volumes of sulfide droplets into smaller areas (Barnes et al., 2016).

Proxies for critical mineralization processes

Particular geological features of the mafic–ultramafic intrusion-hosted Ni–Cu–PGE mineral system are summarized in Table 2 (and Fig. 1), highlighting the critical processes deemed essential for the formation of mineralized deposits. The Mineral System Tree (Fig. 1) is a diagrammatic representation of all the important components of the mineral systems analysis. The mappable proxies in the lower section of the Mineral System Tree represent recommended GIS map layers that may guide future data collection relevant to exploring mafic–ultramafic intrusion-hosted Ni–Cu–PGE deposits. Only proxies with sufficient data on a regional scale were selected for inclusion in the MSA. These proxies, along with the rationale for their selection, are discussed below in the context of the critical and constituent processes identified in the mineral systems analysis.

Source

As summarized in Schulz et al. (2014) and Barnes et al. (2016), mafic–ultramafic intrusion-related Ni–Cu–PGE deposits are high-flux systems that require the eruption of large volumes of hot magmas over a short time. These magmas are often attributed to mantle plume activity, although other geodynamic settings may also play a role in their generation.

The geological proxy for high-flux mafic–ultramafic magmatic systems is the occurrence of large areas of mafic–ultramafic rocks, often associated with felsic igneous rocks (e.g. rhyolite and dacite), indicating bi-modal volcanism. Large igneous provinces (LIPs), which commonly represent such magmatic events, are extensive geological units typically characterized by dyke swarms. The mafic–ultramafic components of granite–greenstone terranes may serve as Archean equivalent of LIPs (e.g. Ernst and Buchan (2003), and references therein). Greenstone belts and LIPs have been mapped in the MSA under 'Tectonic units' (the 'Greenstone belts' and 'Large igneous provinces (LIP)' layers). However, note that the 'Greenstone belts' layer is generalized and includes granitic, felsic and sedimentary rock components, applying only to the Pilbara and Yilgarn Cratons. Substantial dyke suites occur beyond mapped LIP areas and are presented under 'Structures' as '1:2 500 000 State interpreted dyke suites', with further refinement using the 'Dykes density – ldke raster' layer. However, these datasets are not comprehensive and do not cover all dykes

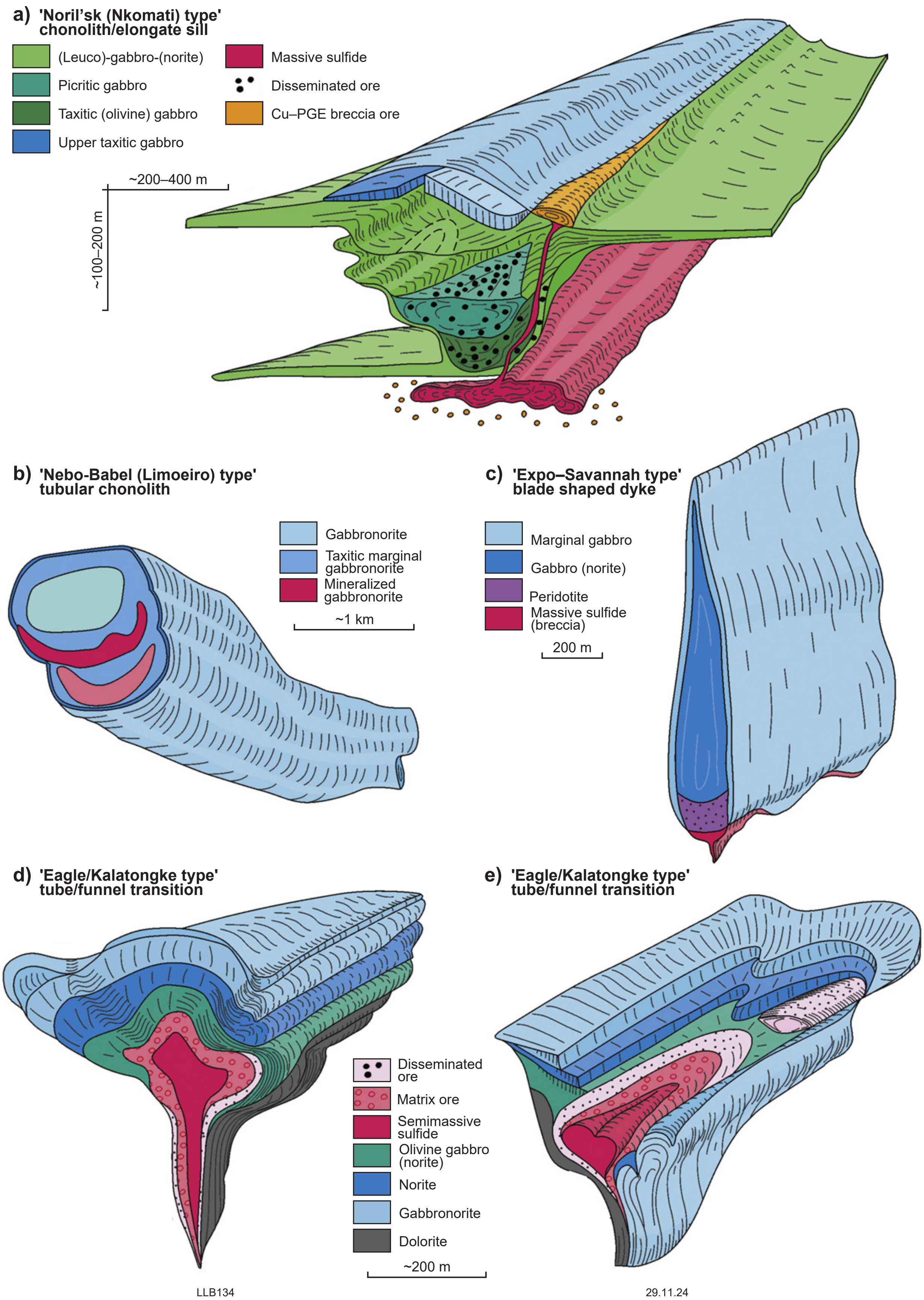

Figure 3. Schematic diagram illustrating different geometries of mafic–ultramafic intrusions, with B and C being Western Australian examples (after Barnes et al., 2016)

Table1. Characteristics of komatiite-hosted vs mafic-hosted Ni–Cu–PGE sulfide deposits (after Barnes et al., 2016)

Attribute	*Komatiite-hosted deposits*	*Mafic intrusion-hosted deposits*
Nature of host silicate magma	Low viscosity, high temperature, fast cooling rate, wide melting range	High viscosity, low temperature, slow cooling rates, narrow melting range (relatively)
Nature of sulfide ore magma	Ni-rich, Cu-poor, extremely low viscosity, narrow melting range	Relatively Ni-poor, Cu-rich, low viscosity, wide melting range
Morphology and geometry of host body and plumbing system	Elongate lava tubes or channels. Predominantly horizontal, and lateral flow processes, vertical feeder dykes are rarely preserved	Tube- or funnel-shaped conduits, flow-through sill-dyke complexes, blade-shaped dykes. Ore formation within long-lived, vertically extensive recharged magmatic plumbing systems
Relationship to host rocks	Thermal/mechanical erosion of floor rocks	Thermal/mechanical erosion of floor and roof rocks, abundant xenoliths and intrusion breccias
'Taxites' and pegmatoidal rocks	Virtually unknown – equivalent may be contaminated pyroxene-rich cumulates	Common 'taxites' – contaminated, vari-textured to pegmatoidal and locally volatile-rich gabbros at intrusion margins and within orebodies, common association with minor hydrous silicate phases
Massive ore disposition	Usually planar, conformable at basal contacts, may inject into floor rocks	Commonly crosscut early marginal rocks of host intrusion and adjacent wall rocks
Breccia ores	Rare – where found, due to melting of floor rocks and gravitational floating of detached xenomelts	Breccia ores common – normal Cu–Ni sulfide intrusion/injection breccias, rarely (as at Noril'sk) external Cu–Pd-rich explosively emplaced breccia/skarn ores
Fractionation of sulfide ore magmas	Minor, manifest as subtle differences between massive ores and matrix/disseminated ores	Commonly, can lead to chemical and mineralogical differentiation of entire orebody at scales from metres to hundreds of metres

Table 2. Critical features of the mafic–ultramafic intrusion-hosted Ni–Cu–PGE mineral system

Critical processes	*Description*
Source	Of mafic–ultramafic magmas
Pathway	Location of lithospheric faults, ancient cratonic blocks and dyke/sill complexes, responsible for transport of mafic–ultramafic magmas through the crust
Chemical trap	Sulfur saturation of previously sulfur undersaturated magma
Chemical and physical trap	Sequestering metals into sulfides
Physical trap	Concentration of metal-rich sulfides
Preservation/modifcation	Of nickel orebodies

in deeper sedimentary basins.

Mineralization is typically hosted in ultramafic cumulate rocks (i.e. the most primitive part of the system; Barnes et al., 2016). Ultramafic cumulates are defined geochemically as rocks containing more than 32 wt% MgO (Barnes, 2006), with high Ni and Cr contents, but low Ti and Al (after Barnes, 2023). The MSA provides maps to help identify cumulate rocks through geochemical classifications such as 'MgO wt >= 32% Mafic ultramafic intrusion SOURCE', 'Mg# Mafic ultramafic intrusion SOURCE', and 'Geochemistry--Cumulate classification SOURCE--ACTIVE PATHWAY', as well as direct observations, e.g. 'Field observations--Cumulate SOURCE--ACTIVE PATHWAY' and 'Field observations – indicator mineral SOURCE'.

Other potential mafic and ultramafic source rocks are mapped in the MSA under 'Lithology', with layers such as 'Ultramafic SOURCE – TRAP', 'Mafic SOURCE – TRAP', and 'Mafic intrusion SOURCE – TRAP'. These maps generally do not cover any subsurface mafic rocks in deep sedimentary basins, but relevant geochemical data from the GSWA database are included under 'Geochemistry', such as 'Geochemistry—Ultramafic' and 'Geochemistry—Mafic'. A subset of these data relevant to this system is provided under 'Geochemistry — mafic–ultramafic intrusion'.

Active pathway

Active pathways transport large amounts of mafic–ultramafic magmas from the upper mantle through the crust, with long-lived lithosphere-scale faulting and dyke propagation playing a fundamental role (Barnes et al., 2016). These transport pathways need to be accessed multiple times by successive magma pulses. Major crustal boundaries, identified through seismic and magnetotelluric surveys, as well as regional geochronological and isotopic data, are mapped in the MSA under 'Structures' as '1:2 500 000 major crustal boundaries' (Martin et al., 2021).

The density of fault intersections, represented by the 'Structural complexity – nsre raster' in the MSA, can help identify long-lived structures in cratonic blocks. Additionally, the presence of mantle-derived rocks such as carbonatite, kimberlite, lamprophyre, and sanukitoid can indicate large-scale structures (MSA layer 'Field observations – mantle-derived rock ACTIVE PATHWAY').

Dyke propagation is a key mechanism for magma transport through the crust, with buoyancy and pressure at dyke tips facilitating upward movement (Barnes et al., 2016). Dyke and sill swarms mapped on or near surface are included in the MSA under 'Structures' as '1:2 500 000 State interpreted dyke suites', with the spatial density of dykes available as 'Dykes density—ldke raster'. However, note that regional dykes have not been fully mapped for deeper sedimentary basin areas.

Cumulate rocks are also critical in identifying active pathways for mineralization. Therefore, combining information on dykes with source-related data on cumulates (e.g. 'Field observations--Cumulate SOURCE--ACTIVE PATHWAY', 'Geochemistry--Cumulate classification SOURCE--ACTIVE PATHWAY' and 'MgO wt >= 32% Mafic ultramafic intrusion SOURCE') can provide further insights into mineralization potential.

Chemical scrubber trap

In mafic–ultramafic intrusion-related Ni–Cu–PGE systems, sulfur undersaturated magmas typically reach sulfur saturation during emplacement, often through the assimilation of sulfur-rich sedimentary rocks (e.g. Arndt et al., 2005; Lightfoot, 2007; Keays and Lightfoot, 2010). Sulfidic sedimentary rocks and evaporites (e.g. Seat et al., 2009) are mapped in the MSA under 'Field observations – sulfidic sedimentary rock TRAP – CHEM SCRUBBER' and 'Evaporites and diapirs SOURCE'. These datasets, however, are not comprehensive, particularly with respect to sulfides within or evaporites in deeper basins.

In some instances, external sulfur introduction may not be required for sulfur saturation, as in Nebo-Babel, where silica addition is suspected to have induced sulfur saturation (Seat et al., 2009; Godel et al., 2011). Sulfides within mafic and ultramafic intrusive rocks are potential indicators of sulfur saturation (MSA layers 'Sulfur wt% ≥1% mafic–ultramafic intrusion TRAP – CHEM SCRUBBER' and 'Field observations—Nickel copper sulfide mineral TRAP—CHEM AND PHYS SCRUBBER' and 'Field observations—Pentlandite TRAP—CHEM AND PHYS SCRUBBER').

Chemical/physical scrubber trap

Once sulfur saturation has occurred, chalcophile metals (Ni, Cu, PGE) from the silicate melt are readily sequestered into sulfide liquids due to their high partitioning into sulfide liquid and solids. In these systems, multiple influxes of magma into host intrusions or source chamber are important, as they allow for magma recharge, replenishing the metals in the melt. Additionally, repeated influxes promote high levels of interaction between silicate and sulfide melts, increasing the likelihood of metal scavenging (Schulz et al., 2014).

A proxy for the degree of physical interaction between the silicate melt and sulfide droplets is the metal sulfide concentration in sulfides (i.e. higher Ni and Cu tenors), as well as the physical presence of magmatic sulfides in the host rocks (e.g. 'Field observations--Pentlandite TRAP--CHEM AND PHYS SCRUBBER' and 'Field observations – nickel copper sulfide mineral TRAP – CHEM AND PHYS SCRUBBER' layers).

Physical throttle trap

Sulfide droplets are precipitated from the silicate melt, accumulating and concentrating as layers of Ni- and/or Cu-rich sulfide minerals. This process typically occurs through chemical mechanisms in response to changes in magma temperature, composition or mechanical mechanisms such as density changes (Barnes et al., 2016). In mafic systems, the mechanism that allows for the precipitation of large volumes of sulfide droplets without corresponding amounts of silicate melt are not well understood (Barnes et al., 2016).

The physical presence of sulfides is evidence of their accumulation, which can be confirmed by direct observation (e.g. in drillcore and thin section), and inferred using electromagnetic conductor data from geophysical surveys. Geochemical mapping of Ni, Cu and PGE in drillholes, along with arsenides mapping (e.g. Le Vaillant et al., 2014), also indicates sulfide accumulation. The MSA includes regional-scale geochemical mapping of maximum grades in exploration drillholes for Ni, Co, Pt and Pd (available under the MSA 'Drillholes—Raster' section). Different cell sizes are used to display the spatial distribution of these elements at various scales. Where sufficient data are available, hill-shaded images showing the number of mineralized drillholes per unit area are also provided to assist in visualizing mineralization trends. Given the limitations and known issues with these datasets (Ormsby et al., 2021), it is strongly recommended to closely examine original exploration reports (identified by unique 'A-Numbers' in the Mineral Exploration Drillholes layer in GeoVIEW.WA) before using this information for detailed work, including exploration targeting.

Modification

Modification, weathering, and preservation are essential considerations in most mineral systems. Erosion is often favourable as it can expose mineral deposits at the surface, but excessive erosion may completely remove the deposit. Similarly, a small amount of cover can protect a mineral deposit from weathering and erosion, while excessive cover can render it uneconomic to extract.

The nature of the regolith is another key consideration. Mapping transported regolith can help identify areas where surface geochemical sampling may not effectively detect anomalous pathfinder elements, especially when combined with regolith depth information. The MSA includes the surface map 'Transported regolith' in the primary data layers. Conversely, recognizing residual regolith overlying mafic intrusion rock units can help focus surface geochemical sampling programs for this style of mineralization (see the MSA 'Residual regolith--Mafic intrusion MODIFICATION' layer).

Conclusion

This Record summarizes the mineral systems analysis of the mafic–ultramafic intrusion-hosted Ni–Cu–PGE system and identifies critical processes for the formation and preservation of mineralization. The key critical processes include: i) formation of large volumes of mafic–ultramafic magmas that will feed the host intrusions; ii) lithospheric-scale structures that facilitate magma transport through the crust and the development of dynamic subvolcanic feeder systems; iii) sulfur saturation; iv) the sequestering of metals into sulfides; v) the concentration of metal-rich sulfides; and vi) modification, weathering and preservation of the original ore body.

We describe links between these processes and the derivation of the geoscience data proxies that have been included in the MSA, as summarized in the Mineral System Tree (Fig. 1). The integration of these proxies can help interpret regional prospectivity and inform exploration strategies for these deposits.

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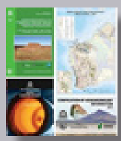

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