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KOMATIITE-HOSTED Ni-Cu-PGE DEPOSITS: A MINERAL SYSTEMS ANALYSIS

LL Grech



Government of Western Australia
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and Safety

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**Geological Survey of
Western Australia**

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Cover image: Journey to the centre of the Kimberley (© 2010 PL Schubert)

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Komatiite-hosted Ni–Cu–PGE deposits: a mineral systems analysis

LL Grech

Abstract

Western Australia hosts world-class examples of komatiite-hosted Ni–Cu–PGE deposits, including Kambalda, Perseverance and Mount Keith. A mineral systems analysis has been performed to define critical and constituent processes controlling their genesis, and mappable proxies for these processes. Critical processes include: (i) formation of komatiitic magmas as a source for metals; (ii) lithospheric-scale structures to transport komatiitic magmas through the crust; (iii) addition of sulfur to magma via crustal assimilation to induce sulfur saturation; (iv) sequestration of metals into sulfide solutions; (v) the physical concentration of metal-rich sulfide solutions; and (vi) structural and hydrothermal modification of the nickel orebodies. The constructed Mineral Systems Tree for komatiite-hosted deposits demonstrates the link between geological processes and their recommended GIS map layers for exploration.

KEYWORDS: komatiite, nickel

Introduction

The Mineral Systems Atlas is an interactive GIS-based platform that collates and delivers map-based geoscience data layers specifically relevant to understanding and exploring for mineral deposits in Western Australia (www.dmirs.wa.gov.au/mineralsystems atlas). Atlas content is systematically defined by applying the mineral systems concept (Wyborn et al., 1994; McCuaig et al., 2010) that 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), and that these critical processes might be recognized from mappable geological features expected to result from them. These geological features ('targeting elements' or 'geological proxies') can be extracted as digital map layers from geoscience datasets and may be used for GIS-based prospectivity studies.

Different mineral systems (e.g. Fraser et al., 2007) are analysed to define the mappable geological proxies for critical mineralizing processes. Structured queries are then used to extract data relevant to those mappable proxies from one or more statewide GSWA geoscience database. These queries are dynamically linked to primary GSWA geoscience data sources and are scheduled to update automatically whenever new data are added, hence Mineral Systems Atlas derived proxy map layers always reflect the current available data.

Komatiite-hosted Ni–Cu–PGE deposits are economically important to Western Australia, and are the primary nickel resource in Australia (Hoatson et al., 2006). The state hosts several world-class examples of such nickel deposits, including Kambalda (5.3 Mt @ 3.8% Ni; Sargent, 2022) and Mount Keith (643.7 Mt @ 0.58% Ni; Sargent, 2022).

The metallogenesis of komatiite-hosted Ni–Cu–PGE mineralization is considered to be fairly well understood, and this mineral systems analysis is informed by existing literature (e.g. Hill, 2001; Leshner and Keays, 2002; Barnes et al., 2004; Hoatson et al., 2006; Barnes and Fiorentini, 2012; Barnes et al., 2016; Le Vaillant et al., 2016), and consultation with subject matter experts.

This contribution describes the reasoning underpinning the analysis of the komatiite-hosted Ni–Cu–PGE mineral system, leading to the definition of mappable proxies that inform the GIS map layers featured in the Mineral Systems Atlas. A brief description of the classification of komatiites is first provided, then results of the mineral systems analysis are presented in graphic form as a Mineral Systems Tree. Further information about the komatiite-hosted Ni–Cu–PGE mineral system is provided in the online Guide to the Mineral Systems Atlas (www.dmp.wa.gov.au/msa/). The information in the Guide and Atlas will be updated based on improvements in our understanding about this mineral system and additions of related geoscience data to the GSWA databases.

Komatiites: classification and characteristics

Burley and Barnes (2019) recently described key physical and chemical properties of komatiites, as summarized below:

"Komatiites are defined as volcanic or subvolcanic rocks derived from melts with liquid compositions >18 wt% MgO (Arndt et al., 2008). Their geochemical and mineralogical compositions reflect anomalously high mantle temperatures that were likely common during the Archean, the age

of almost all known examples of komatiites (e.g. Arndt et al., 2008; Herzberg et al., 2010). Many komatiites show internal differentiation into two main zones, an upper olivine spinifex-textured zone and a lower olivine cumulate zone, which are widely referred to as A- and B-Zones, respectively (Hill et al., 1988). Olivine spinifex textures are typically formed by relatively rapid in situ crystallization of olivine, usually at the top of a flow, whereas olivine cumulates are formed by slower crystallization of olivine, with crystals accumulating and settling at the base of a flow or sill (Hill et al., 1988). Cumulates can be divided into orthocumulates, mesocumulates and adcumulates on the basis of the tightness of their crystal packing, that is, how much liquid was trapped between the phenocrysts (Wager et al., 1960). Primary mineral assemblages in komatiites are always altered to some degree (Barnes, 2006; Arndt et al., 2008). Mineral alteration assemblages vary according to factors including the bulk composition of the original lava, metamorphic temperature–pressure conditions, or interaction with metamorphic or hydrothermal fluids (Gole et al., 1987; Barnes, 2006; Arndt et al., 2008; Table 1). Hence, it is important to base geochemical identification of komatiites on the contents of elements such as Si, Cr, Al, Ti, Fe, Ni and Mg – initial quantities of which are usually retained in komatiites – and incompatible trace elements such as rare earth elements (REE) and high field strength elements (HFSE) (Hill et al., 1988; Barnes et al., 2004; Barnes, 2006). This is important because mantle source information and exploration vectoring tools can be derived from these elements. For example: 1) MgO/FeO ratios are used to estimate primary komatiite liquid and olivine compositions (Barnes et al., 2004; Barnes, 2006); 2) Al₂O₃/TiO₂ ratios are used to classify komatiites as Al-depleted, Al-undepleted or Al-enriched, which may inform assumptions and interpretations regarding their mantle source compositions and geodynamic processes (Nesbitt et al., 1979; Sproule et al., 2002; Wilson, 2003); 3) incompatible trace element ratios (e.g. Zr/TiO₂, La/Sm, Th/Nb) are used to assess the extent to which magmas have assimilated crustal materials (e.g. Perring et al., 1996; Barnes et al., 2004; Barnes, 2006); 4) Ni/Ti and Ni/Cr ratios are used to distinguish magma pathways favourable for nickel sulfide mineralization, such as olivine–adcumulate-rich channels, from low energy depositional environments like channel flanks, which are typically unfavourable for mineralization (e.g. Barnes et al., 2004).

Barnes et al. (2004) described five major volcanic facies that are common constituents of komatiitic flow fields (Table 2): 1) thin differentiated flows (TDF); 2) compound sheet flows with internal pathways (CSF); 3) dunitic compound sheet flows (DCSF); 4) dunitic sheet flows (DSF); 5) layered lava lakes and/or sills (LMLS). Of these, only DCSF and CSF facies are known to host nickel sulfide mineralization. Both of these facies represent high-flow magma pathways characterized by olivine cumulates and can be identified by their elevated Ni/Ti and Ni/Cr ratios and low Cr contents (Barnes et al., 2004)."

Critical mineralization processes

Features of the komatiite-hosted Ni–Cu–PGE mineral system are summarized as a list of critical processes (Table 3) and as a more detailed Mineral Systems Tree, which is a diagrammatical representation of all the important components of the mineral systems analysis. Mappable proxies in the lower section of the Mineral Systems Tree are recommended GIS map layers that may guide future collection of data relevant to exploration for komatiite-hosted deposits.

Six critical processes have been identified for komatiite-hosted Ni–Cu–PGE mineralization. Their associated mappable proxies are discussed here in more detail.

Source

Komatiite magma is the product of a high degree of mantle melting of asthenospheric mantle and is recorded almost exclusively in Archean cratons (Arndt et al., 2008), which in Western Australia includes the Yilgarn and Pilbara Cratons. Today these magmas are areas of laterally extensive (typically intensely altered) ultramafic rocks, which are commonly associated with thick sequences of mafic rocks and felsic volcanic rocks, which are areas with bimodal volcanism and interpreted to be related to lithosphere-scale rifting.

Table 1. General characteristics of A-Zone and B-Zone komatiites (summarized from Barnes, 2006; table from Burley and Barnes, 2019)

	<i>A-Zone komatiites</i>	<i>B-Zone komatiites</i>
Primary igneous textures	Spinifex textures	Cumulate textures (adcumulate, mesocumulate and orthocumulates)
Primary mineralogy	Olivine or pyroxene, or both	Olivine
Geochemical characteristics	Typically 20–32 wt% MgO Higher Al ₂ O ₃ , TiO ₂ and SiO ₂	Typically >32 wt% MgO Lower Al ₂ O ₃ , TiO ₂ and SiO ₂
Typical mineralogy in CO ₂ -rich conditions – greenschist facies	Tremolite-chlorite-dolomite	Quartz-magnesite-dolomite-chlorite or talc-chlorite-dolomite-magnesite (orthocumulates and mesocumulates) or talc-magnesite (adcumulates)

Table 2. Descriptions of komatiite volcanic facies (Barnes et al., 2004; table from Burley and Barnes, 2019)

<i>Facies</i>	<i>Description</i>	<i>Type examples</i>
Thin differentiated flows (TDF)	Multiple compound spinifex-textured flows; generally less than 10 m thick, with internal differentiation into spinifex and cumulate zones.	Munro Township (Pyke et al., 1973)
Compound sheet flows with internal pathways (CSF)	Compound thick cumulate-rich flows, with central olivine-rich lava pathways flanked by multiple thin differentiated units, from tens of metres to about 200 m maximum thickness.	Silver Lake Member at Kambalda (Leshner et al., 1984)
Dunitic compound sheet flows (DCSF)	Thick olivine-rich sheeted units with central lenticular bodies of olivine adcumulates, up to several hundred metres thick and 2 km wide, flanked by laterally extensive thinner orthocumulate-dominated sequences with minor spinifex. CSF and DCSF correspond to "Flood Flow Facies" of Hill et al. (1995).	Perseverance and Mt Keith (Hill et al., 1995)
Dunitic sheet flows (DSF)	Thick, laterally extensive, unfractionated sheet-like bodies of olivine adcumulates and mesocumulates, in some cases laterally equivalent to layered lava lake bodies.	Southern section of the Walter Williams Formation (Gole and Hill, 1990; Hill et al., 1995)
Layered lava lakes and/or sills (LLLS)	Thick, sheeted bodies of olivine mesocumulates and adcumulates with lateral extents of tens of kilometres, with fractionated upper zones including pyroxenites and gabbros, up to several hundred metres in total thickness.	Kurrajong Formation (Gole and Hill, 1990; Hill et al., 1995)

High-flux magma pathways are important for the formation of significant mineralization (Hill, 2001; Barnes et al., 2004; Barnes and Fiorentini, 2012; Barnes et al., 2016). Olivine cumulates – rocks with MgO typically >32% (Barnes, 2006) – are often documented in high-flux magma pathways (Hill, 2001; Barnes et al., 2004; Barnes, 2006). Other geochemical and textural indicators of these pathways include: compound sheet flows with internal pathways or dunitic compound sheet flows, and elevated Ni/Ti and Ni/Cr ratios and low Cr contents (Barnes et al., 2004). Mapping komatiite thickness and morphology may assist with locating high-flux magma pathways. Not only is the formation of high-flux magma pathways important for this first critical process, but their formation is also important for all three 'trap' processes that follow (chemical scrubber, chemical/physical scrubber and physical throttle traps). As explained in Barnes et al. (2016), these environments are beneficial for a number of reasons, including that they can promote assimilation of wall rocks leading to the addition of external sulfur, help concentrate large volumes of sulfide droplets into smaller areas, and encourage interaction between large amounts of magma and sulfide droplets, causing higher ore tenors (Barnes et al., 2016).

Active pathway

Active pathways transport komatiitic magma from the mantle through the crust, commonly via lithospheric-scale faults (Beresford et al., 2007; Begg et al., 2009; McCuaig et al., 2010; Barnes and Fiorentini, 2012; Barnes et al., 2016). Mapping these major crustal boundaries can be done through seismic (reflection and passive) and magneto telluric surveys, and by interpreting gradients in regional geochronological and isotopic data. Byproducts of crustal scale structures that could also be used as proxies include carbonatite, kimberlite, lamprophyre and sanukitoid intrusions, and rift-related volcanic rocks, such as rhyolite and dacite. Ultramafic rocks also provide evidence for major structures.

Chemical scrubber trap

Leshner (1989) proposed that komatiitic magmas are sulfur-undersaturated, with saturation being reached during their emplacement into the crust. Sulfur saturation occurs via assimilation of magma with continental crust and sulfur-rich sediments (Leshner, 1989).

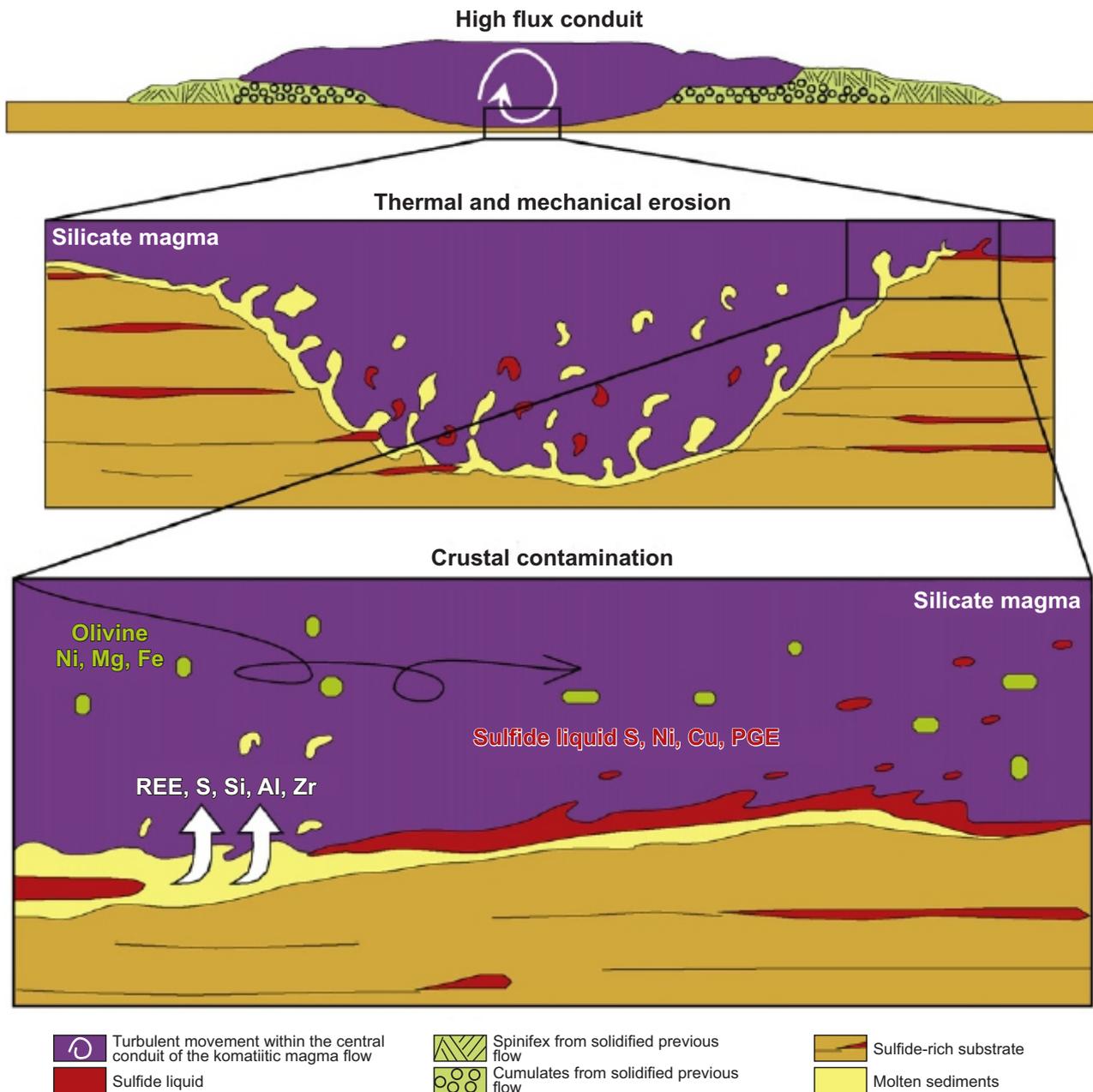
High-flux magma pathways are a perfect environment for sulfur saturation (Barnes et al., 2016). Geochemical proxies for sulfur saturation are also prime indicators for nickel sulfide mineralization (e.g. Perring et al., 1996; Barnes et al., 2004; Barnes, 2006). Their geochemical proxies compare elements that are enriched in the continental crust (e.g. Zr, Th, La and other light REE) with elements that are enriched in the mantle (e.g. Ti, Y and heavy REE). The best proxies are expressed as ratios, for example Zr/TiO₂, La/Sm, Th/Nb and Th/Yb (Barnes, 2006). Another indicator that sulfur saturation may have occurred is high amounts of sulfides within mafic and ultramafic rocks, as measured by sulfur abundance or the direct observation of visible sulfides in fresh rock. The local absence of sulfidic rocks near komatiites, in an area that is otherwise regionally abundant, is an indirect method for interpreting the assimilation of sulfides into komatiite magmas.

Chemical/physical scrubber trap

After sulfur saturation, metals (Ni, Cu, PGE) from the silicate melt can sequester into sulfide liquids (Fig. 1). As explained further in Le Vaillant et al., 2016, a high level of interaction between silicate magmas and sulfide droplets is required in this process (i.e. more interaction means a higher chance for metals from the silicate melt to sequester into sulfide droplets; Campbell and Naldrett, 1979; Naldrett, 1999), and efficient mixing to encourage equilibrium (Leshner and Campbell, 1993; Robertson et al., 2016). These two processes increase the concentration of sulfides to make a deposit economically viable (Le Vaillant et al., 2016).

Table 3. Critical features of the komatiite-hosted Ni-Cu-PGE mineral system

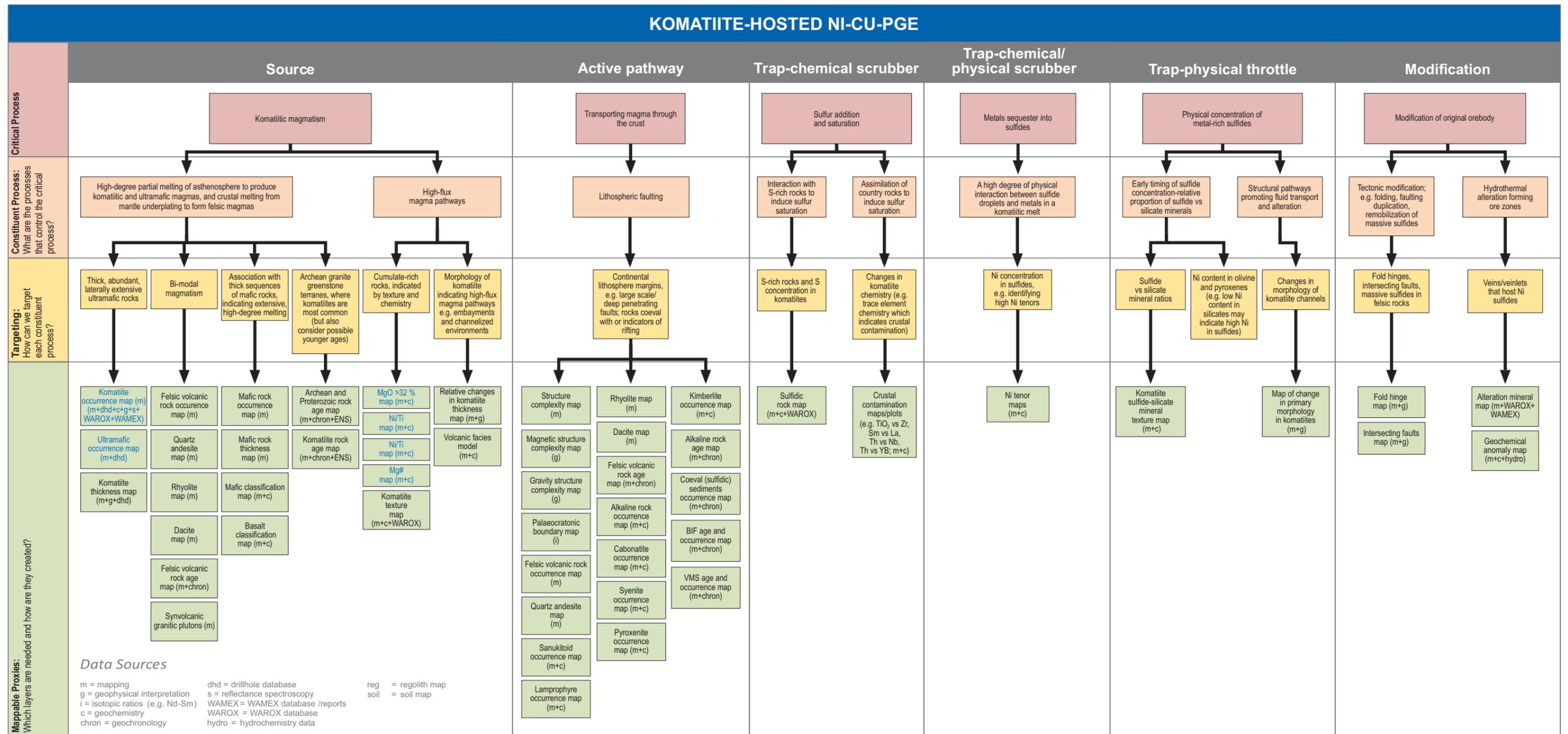
Critical process	Description
Source	Komatiite magma
Pathway	Lithospheric faults and continental lithosphere margins, responsible for transport of komatiitic magma through the crust
Chemical trap	Addition of sulfur and sulfur saturation of previously sulfur undersaturated magma
Chemical and physical trap	Sequestering metals into sulfides
Physical trap	Concentration of metal-rich sulfides
Modification	Of nickel orebodies



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Figure 1. Schematic diagram of the formation of komatiite-hosted Ni-Cu-PGE deposits (from Le Vaillant et al., 2016)



Blue text = geological proxy layer available in the Atlas
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Figure 2. The Mineral Systems Tree is a graphical display of a mineral systems analysis showing the link between critical/constituent processes and their recommended targeting features and GIS layers

A proxy for a high degree of physical interaction between the silicate melt and sulfide droplets is the metal concentration in sulfides, that is Ni tenor (concentration of Ni metal in the mineral).

Physical throttle trap

Sulfide droplets are precipitated from the silicate melt, where they accumulate and concentrate as layers of metal-rich sulfide minerals. This typically occurs via chemical processes (in response to a change in host magma temperature or composition), or mechanical processes (typically changes in density) (Barnes et al., 2016). Areas of change in komatiite channel morphology can represent areas where heavier sulfides may have accumulated.

If sulfides concentrate early during crystallization of the komatiite magma, this may be reflected by lower Ni values in olivine and pyroxenes and higher Ni values in the sulfides (e.g. Barnes and Fiorentini, 2012). Mappable proxies include a change in the proportion of sulfides vs silicate minerals in komatiites.

Modification

Deformation of komatiitic host rocks and remobilization of massive sulfide ore zones are important in understanding present 3D geometries of nickel sulfide deposits. Faults and shear zones intersecting primary orebodies may remobilize massive sulfides away from the original site of magmatic deposition (e.g. massive sulfide ore shoots at the Harmony deposit; Duuring et al., 2007). Remobilized massive sulfides may exist in fold hinges, along fault zones, and be hosted in exotic areas, such as neighbouring felsic volcanic rocks.

Hypogene fluid alteration of komatiites may remobilize metals and form sulfide veins or veinlets away from the primary nickel sulfide orebody, for example, hydrothermal fluids rich in arsenic are present at the Sarah's Find deposit (Mount Keith mining area), with primary Ni–Co–Pd and Pt being remobilized and precipitated elsewhere as arsenides or sulfarsenides, and a Ni–Co–As–Pd–Pt geochemical footprint detectable ~1800 m away from the primary massive sulfide deposition site (Le Vaillant et al., 2014). Mapping the distribution of these alteration minerals and recognizing their geochemistry can be useful tools for identifying such alteration.

Conclusion

This record summarizes a mineral systems analysis of the komatiite-hosted Ni–Cu–PGE system, explains the links between processes involved in their formation and provides a set of GIS layers that can inform exploration strategies for these deposits, as summarized in the Mineral Systems Tree (Fig. 2). We emphasise the requirement to find proxies for the following critical processes: (i) genesis of komatiitic magmas, which are the source for Ni–Cu–PGE metals; (ii) lithospheric-scale faulting that are transport pathways for komatiitic magmas through the crust; (iii) addition of sulfur to magmas via crustal assimilation to induce sulfur

saturation; (iv) sequestration of metals into sulfide solutions; (v) physical concentration of metal-rich sulfide solutions by gravitational settling or catchment in trap positions; and (vi) structural or hydrothermal modification of nickel orebodies.

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