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# Review of lithogeochemical exploration tools for komatiite-hosted Ni-Cu-(PGE) deposits

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ABSTRACT

High grade type 1 (stratiform contact) Komatiite-hosted Ni-Cu-(PGE) deposits are composed of extremely valuable but small and often deep-seated ore bodies. This paper describes, reviews and compares the current exploration techniques for these challenging exploration targets, with new scientific advances and recently developed exploration tools including latest studies on the nature and size of secondary hydrothermal haloes surrounding primary magmatic deposits. The focus is on understanding at which scales these various tools should be used and compare their accuracy. The scale, geological context and density of the available data will affect the effectiveness of different geochemical exploration tools, therefore the uncertainties on our understanding of these criteria will have a significant impact on the outcome of exploration protocols. At the deposit scale, many effective traditional geochemical indicators (e.g., Ni/Cr, PGE variations) as well as many geological indicators, potentially extending 50 to 450 m from ore, will be rendered inadequate by structural deformation of the system. In such cases, hydrothermal haloes will still be effective up to km scale and should be favoured, especially when combined with EM surveys, as demonstrated by case studies in deposits in Western Australia such as Spotted Quoll in the Forrestania greenstone belt, Maggie Hays and Emilie Ann in the Lake Johnson greenstone belt, and Harmony in the Agnew-Wiluna greenstone belt. When stepping up to prospect scale, indicators of favourable tectonic settings, crustal contamination and magmatic processes will be more useful, in particular the use of ratios of Ni, Ti, Zr and Cr that are immobile during alteration and moderate degrees of weathering and can be detected using portable XRF. Such techniques will in some cases allow the generation of regional targets. In any case, and whatever the scale, the best exploration outcomes rely on a smart combination of the various techniques described here, along with a hint of luck.



**Contents**



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## 1. Introduction

A significant proportion (currently about 60%) of the world's nickel is produced from Fe-Ni-Cu sulphides associated with mafic and ultramafic magmatic intrusions and flows (Naldrett, 2004; Mudd, 2010). The remaining nickel production is almost entirely from limonitic and saprolitic laterite deposits, commonly formed by weathering of ultramafic rocks (Golightly, 1981; Barnes and Lightfoot, 2005). Komatiite-hosted Ni-Cu-(PGE) deposits (Type I, Lesher (1989); Lesher and Keays (2002)) are particularly valuable deposits, often composed of small, high-grade (with metal tenors up to 20% Ni) ore lenses, often blind to most current exploration techniques, making them particularly challenging exploration targets. Most exploration techniques used nowadays for komatiite-hosted Ni-Cu-(PGE) deposits, particularly geochemical ones, are based on existing knowledge of the processes at play during their genesis combined with purely empirical approaches. In this study, we firstly review these various genetic processes and their link to current exploration protocols. Then we describe recently developed techniques, particularly those based on hydrothermal alteration haloes around magmatic komatiite-hosted Ni-Cu-(PGE) deposits, which enlarge the detectable footprint of these notably difficult targets. Finally we address the knowledge gap in our understanding of how these new exploration tools and more traditional geochemical and geophysical ones relate to each other, and discuss how their uses could be combined at various scales for effective exploration targeting for komatiite-hosted Ni-Cu-(PGE) deposits.

## 2. Current understanding of komatiite-hosted Ni-Cu-(PGE) ore-forming processes and associated exploration tools

### 2.1. Ore forming processes

A widely accepted hypothesis for the formation of komatiite-hosted magmatic Ni-Cu-(PGE) deposits incorporates three main processes (Fig. 1):

(1) The komatiite magma needs a rapid transport mechanism in order to reach the crust without extensive olivine fractionation, where it will assimilate additional sulphide by

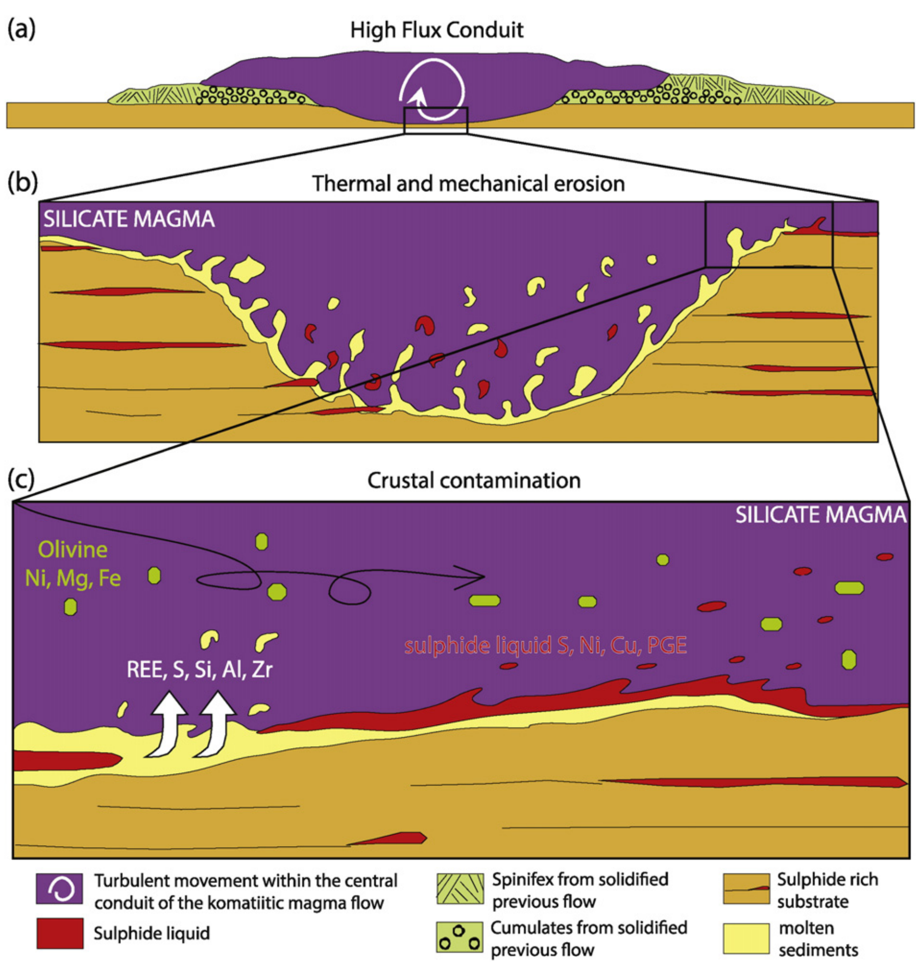


**Fig. 1.** Schematic illustration of the necessary conditions and processes for the genesis of komatiite-hosted Ni-Cu-(PGE) deposits.

thermomechanical erosion of crustal rocks. In the case of komatiites, the sulphide source is often believed to be the sulphide-rich exhalative and/or sedimentary rocks immediately beneath the mineralised lava flow: this is the substrate erosion model (Lesher, 1983; Huppert et al., 1984; Lesher et al., 1984; Groves et al., 1986; Lesher and Groves, 1986b; Lesher and Arndt, 1995; Bekker et al., 2009; Fiorentini et al., 2012a).

(2) Chalcophile elements in the silicate melt partition into sulphide droplets. In order to be concentrated at an economic level, the sulphide droplets need to react with a sufficient amount of magma (Campbell and Naldrett, 1979; Naldrett, 1999) and to be efficiently stirred to enhance equilibration (Lesher and Campbell, 1993; Robertson et al., 2015). Thus, a common feature for Ni-Cu-(PGE) deposits is the presence or proximity of a magma conduit or flow pathway (Lesher et al., 1984; Lesher, 1989; Barnes et al., 2015).

(3) Finally, these sulphide droplets need to be concentrated in important quantities in a restricted locality to form ore bodies (Campbell and Naldrett, 1979; Naldrett, 1999). This concentration is generally thought to be achieved by gravitational settling of dense sulphide droplets to the bottom of komatiite flows (Naldrett, 1966; Ewers and Hudson, 1972), or freezing of dense sulphide liquid layers entrained at the base of the magmatic flow (Lesher and Campbell, 1993).

All these primary magmatic processes leading to the genesis of komatiite-hosted Ni-Cu-(PGE) deposits have been extensively studied and reviewed over the years (Lesher, 1989; Lesher and Keays, 2002; Naldrett, 2004; Barnes, 2006b; Lesher and Barnes, 2009), leading to the development of a wide range of exploration tools. Of these, lithogeochemical techniques are particularly valuable where primary magmatic textures and mineralogy are obscured by alteration, metamorphism and/or weathering. In such cases certain combinations of trace elements can preserve primary magmatic signals and serve as exploration tools.

### 2.2. Current exploration methods

Type I (stratiform contact) komatiite-hosted Ni-Cu-(PGE) deposits are challenging targets, both at the regional and at the deposit scale (McCuaig et al., 2010). Predictive techniques use the understanding of ore genetic processes to predict the location of ore deposits, while detective techniques directly evaluate their presence. Predictive techniques are the main targeting methodology when exploring at the craton- to terrane-scale, based on favourable tectonic setting and volcanic environment (McCuaig et al., 2010; McCuaig and Hronsky, 2014). Detection techniques, such as down-hole electromagnetic and Ni/Cr geochemical haloes, become increasingly more effective as exploration evolves from regional scale, all the way to camp, prospect and deposit scale. However, both the predictive and detective techniques that have been developed in exploration targeting for komatiite-hosted systems over the last four decades have only had limited success. A summary of all these techniques is presented in Table 1.

#### 2.2.1. Predictive techniques at regional scale

When exploring at the regional scale, explorers look for (1) favourable tectonic environments along with (2) the most prospective geological setting.

**Table 1**
Summary of the various exploration tools described in this paper.

| Regional scale | Camp to prospect scale | Deposit scale |
|---|---|---|
| ***Favourable tectonic settings:*** | ***Channelised volcanic environments:*** | ***Evidences of sulphide accumulation and/or extraction:*** |
| Craton boundaries — *Beresford et al. (2007); Begg et al. (2010); McCuaig et al. (2010); Mole et al. (2013, 2014)* | Prediction of prospective volcanic environments — *Barnes and Brand, 1999; Barnes et al. (2004a); Lesher et al. (2001); Fiorentini et al. (2012b); Le Vaillant et al. (2014)* | Positive and negative anomalies in chalcophile elements (Ni, Cu, Co and PGE) whole rock and Ni in olivine — *Barnes et al. (1988a); Barnes and prichard, (1993); Lesher et al. (2001)* |
| Inverted continental rift zones — *Beresford et al. (2007); McCuaig et al. (2010); Fiorentini et al. (2012b)* | Exploration tool: Ni/Ti vs Ni/Cr diagrams, potentially using pXRF data *(Le Vaillant et al. (2014)* | Ruthenium depletion in chromite grains – possible applications in lateritic terranes — *Fiorentini et al. (2008); Locmelis et al. (2011, 2013);* |
| *Exploration tools:* Magnetotellurics, Aeromagnetics,<br>Seismics, Gravity, Sm–Nd model–age maps, Lu–Hf isotopes on zircons; the last two are the only techniques which image this architecture through time and identify palaeo–sutures<br>*(Deen et al. (2006); Champion and Cassidy, (2007, 2008); Begg et al. (2009); McCuaig et al. (2010); Mole et al. (2012, 2014); Perring et al. (2015a, b)* | ***Evidences of crustal contamination:***<br>Sulphur isotope analyses to test crustal assimilation models — *Fiorentini et al. (2012a)*<br>Anomalous enrichment in incompatible elements such as Zr, Th, LREE — *Lesher et al., 2001; Barnes and Hill, (2004b); Fiorentini et al. (2012b)*<br>Possible pervasive contamination signals in certain cases (e.g. Black Swan, Perseverance) — *Barnes et al. (1988c, 2004a, 2007); Barnes and Fiorentini, (2012);* | *Exploration tool:* whole rock analyses, Laser ablation ICP–MS analyses of olivines and chromite to evaluate their Ni or Ru content<br>*Example: Subtle PGE enrichments and depletion signals in host komatiite units at the Long Victor and Maggie Hays deposits, Western Australia, up to 400 m away from massive sulphides (Barnes et al. (2013); Heggie et al. (2012).* |
| ***Areas of enhanced magmatic flux:***<br>High proportions of high MgO komatiite magmas, and abundance of strongly adcumulate olivine–rich cumulates — *Barnes and Fiorentini, (2012)* | *Exploration tools:* Laboratory geochemical analyses, portable XRF (pXRF) analyses potentially directly on the field *(Le Vaillant et al. (2014)*<br>*Example: Presence of a pervasice contamination signal in komatiite units of the Black Swan komatiite complex, as well as the Perseverance ultramafic complex, Western Australia (Barnes et al. (1988b, 2004a)* | ***Empirical detection tools:***<br>Use of Ni/Cr to delineate ore–related channels — *Barnes and Brand, (1999); Barnes et al. (2013)*<br>*Example: delineation of ore shoots around the Kambalda Dome, Western Australia (Barnes and Brand, (1999)*<br>Airborne and down hole Electromagnetic surveys<br>*Example: The Nova discovery (Western Australia) was made when testing a large and strong EM anomalie (ASX Announcement – 26.07.2012)* |
| *Exploration tools:* Regional airborne aeromagnetic surveys<br>*(Barnes et al. (2004a); Grguric and Riley, (2006); Fiorentini et al. (2007)* | ***Evidences of sulphide accumulation and/or extraction:***<br>Positive and negative anomalies in chalcophile elements (Ni, Cu, Co and PGE) whole rock and Ni in olivine — *Barnes et al. (1988a); Barnes and prichard, (1993); Lesher et al. (2001)* | ***Hydrothermal Ni–As–PGE haloes:***<br>Presence of nickel arsenides (gersdoffite mainly) in veins or within a plan of foliation creating a geochemical signal (enrichment in Ni, As, pd and Pt) extending up to 1,780 m away from massive nickel–sulphides. — *Le Vaillant, (2014); Le Vaillant et al. (2015a,b)* |
| *Example: The Nebo Babel deposit in the West Mustgrave, Western Australia, was discovered using lithospheric architectural targeting combining areas presenting evidences of major focused mantle–derived magmatism with anomalous lithospheric architecture (boundary of the Yilgarn craton, and convergence of multiple faults including the Mundrabilla fault) (Pers. Comm. John Hronsky)* | *Exploration tool:* whole rock analyses, Laser ablation ICP–MS analyses of olivines to evaluate their nickel content<br>*Examples: Low Ni content of olivines in the Kambalda Dome komatiite flows and in the Perseverance camp, Western Australia (Lesher et al. (1981); Barnes et al. (1988a); Anoumalous positive and negative PGE concentrations in the komatiite basalt of the Raglan camp, Northern Quebec (Barnes and Picard, (1993); Lesher et al. (2001).* | *Example: Hydrothermal geochemical halo obseved surrounding the Miitel and the Sarah's Find deposits, Western Australia (Le Vaillant et al. (2015a,b)* |

(1) For komatiite-hosted Ni-Cu-(PGE) deposits, favourable tectonic environments are represented by large crustal scale structures favouring magma flow from the mantle to the crust, such as craton boundaries at the time of plume impingement (Beresford et al., 2007; Begg et al., 2010; McCuaig et al., 2010; Mole et al., 2013; Mole et al., 2014) and continental rift zones subsequently inverted by polyphase deformation (Beresford et al., 2007; McCuaig et al., 2010; Fiorentini et al., 2012b) (Fig. 2). In order to image trans-lithospheric faults, numerous geophysical techniques are in use, such as magnetotelluric, aeromagnetic, seismic and gravity profiles. However, geophysical techniques only provide a snapshot of the current lithospheric architecture, which in deformed terrains - such as the ones where komatiites are generally explored for - may have been substantially modified since the time of ore formation. That degree of uncertainty can be reduced through the use of spatially constrained isotopic terrane mapping. Maps of Sm-Nd (εNd) model ages reflect the age of the pre-existing lower crust and can indicate the presence

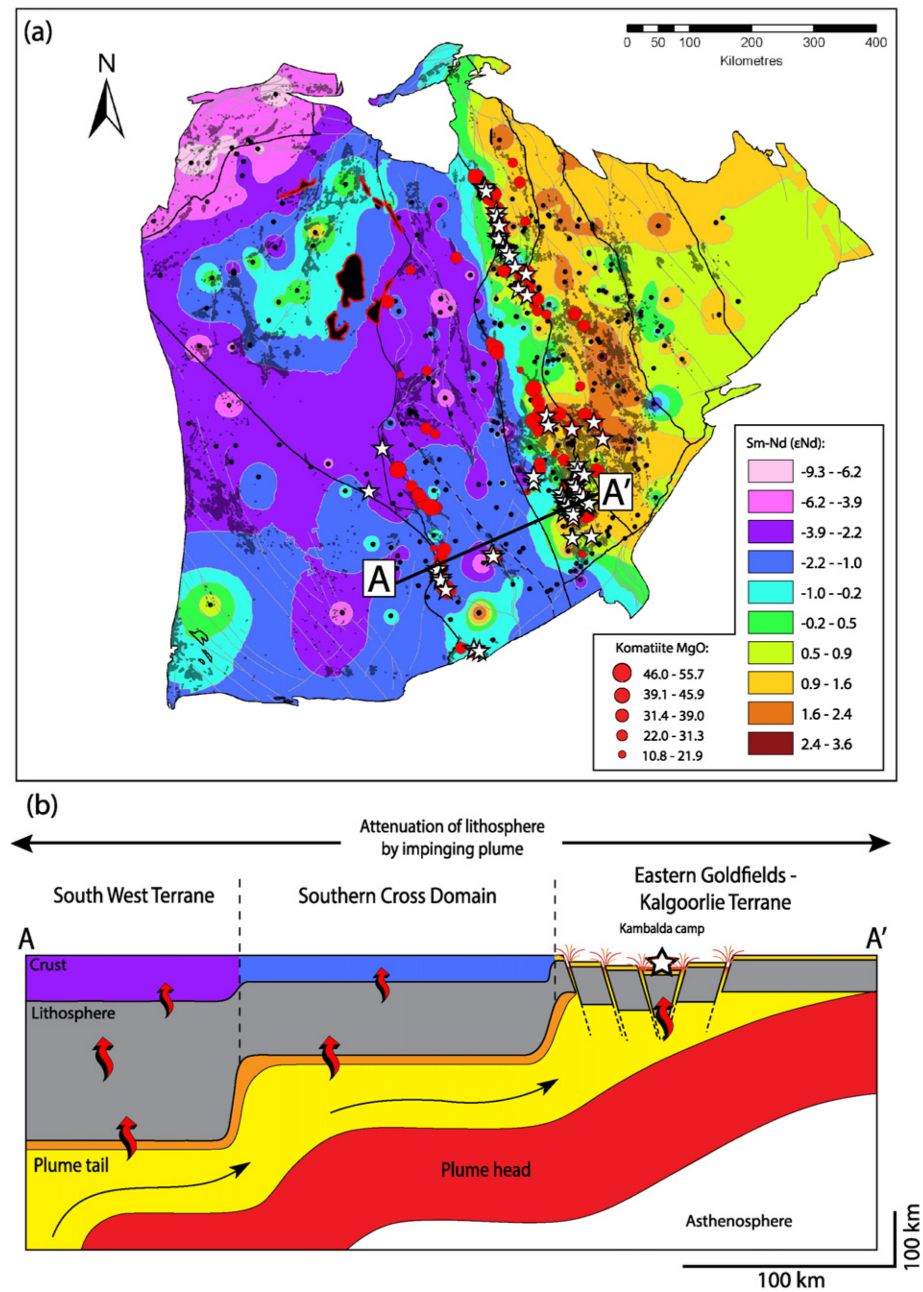


**Fig. 2.** (a) Sm-Nd (εNd) isotopic map (geometric interval) highlighting the internal structure of the Yilgarn craton, Western Australia, and showing the location of komatiite-hosted nickel deposits (white stars). (b) Interpreted lithospheric cross-section based on the Sm-Nd isotopic mapping. The thicker, older crust to the west is inferred to have focused the plume into the shallower area to the east as demonstrated here. This either created a set of rift-related terranes in the Kalgoorlie–Kurnalpi Terranes or reactivated a previous margin, which allowed high flux passage of hot, pre-existing komatiitic magmas to the surface. A similar process is inferred to have formed the c. 2.9 Ca komatiites and associated deposits in the Southern Cross Domain, but this cannot be proven using Sm–Nd isotopes as this map only covers the 2.8–2.6 Ga period. The approximate thickness of developed Archaean lithosphere (c. 250–150 km) was taken from Boyd et al. (1985) and Begg et al. (2009). The approximate scale of the plume head (c. 1600 km), tail (200–100 km) and thickness (150–100 km) were taken from Campbell et al. (1989) and Barnes et al. (2012). These values are proxies based on modern analogues and experiments.
Adapted from Mole et al. (2013).

of ancient craton boundaries (Fig. 2). The addition of Lu-Hf isotopic data from well-dated zircons can add an additional dimension of time combined with information on the magmatic source, allowing craton margin positions to be tracked through time (Deen et al., 2006; Champion and Cassidy, 2007, 2008; Begg et al., 2009; Mole et al., 2012; Mole et al., 2014). Currently, aeromagnetic and geological maps are still the main tools in practice to identify favourable tectonic settings and host lithologies, at a range of scales. For example, Perring (2015a, 2015b) have proposed the existence of accretionary growth faults, recognisable in regional magnetic and gravity patterns, as primary controls on the location of mineralised dunite channels in the Agnew-Wiluna greenstone belt. However, in poorly exposed terrain typical of Archaean greenstone belts, there is a high rate of false positive anomalies created when interpreting mapped lithologies (i.e., structures interpreted as mantle-tapping, which are in fact limited to the upper crust) (McCuaig et al., 2010).

(2) When exploring for komatiite-hosted Ni-Cu-(PGE) deposits, explorers look for areas of enhanced magmatic flux, using elevated proportions of high-MgO komatiite magmas and abundance of strongly olivine mesocumulate-adcumulate rocks as a proxy (Lesher et al., 1984; Lesher, 1989; Hill et al., 1995; Lesher and Keays, 2002; Arndt et al., 2008; Barnes and Fiorentini, 2012). Regional airborne aeromagnetic data allow the identification of these favourable lithologies. This was one of the main exploration tools during the nickel boom (1966–1971) in Western Australia (Woodall and Travis, 1969; Ross and Travis, 1981; Marston, 1984; Hronsky and Schodde, 2006). Where these rocks are serpentinised, they generate strong bulls-eye magnetic anomalies (e.g., Mount Keith deposit, Agnew-Wiluna greenstone belt, Yilgarn craton, Western Australia (Burt and Sheppy, 1975; Grguric and Riley, 2006; Fiorentini et al., 2007). However, this detection technique fails where the ultramafic rocks are converted to non-magnetic talc-carbonate assemblages, as they very commonly are in Archaean settings (such as deposits around the Widgiemooltha and Kambalda Domes, Norseman-Wiluna greenstone belt, Western Australia (Barnes et al., 2004b).

Combination of a favourable tectonic environment such as a trans-lithospheric fault with areas of high magmatic flux within a large igneous province is a highly favourable indicator of nickel endowed mining

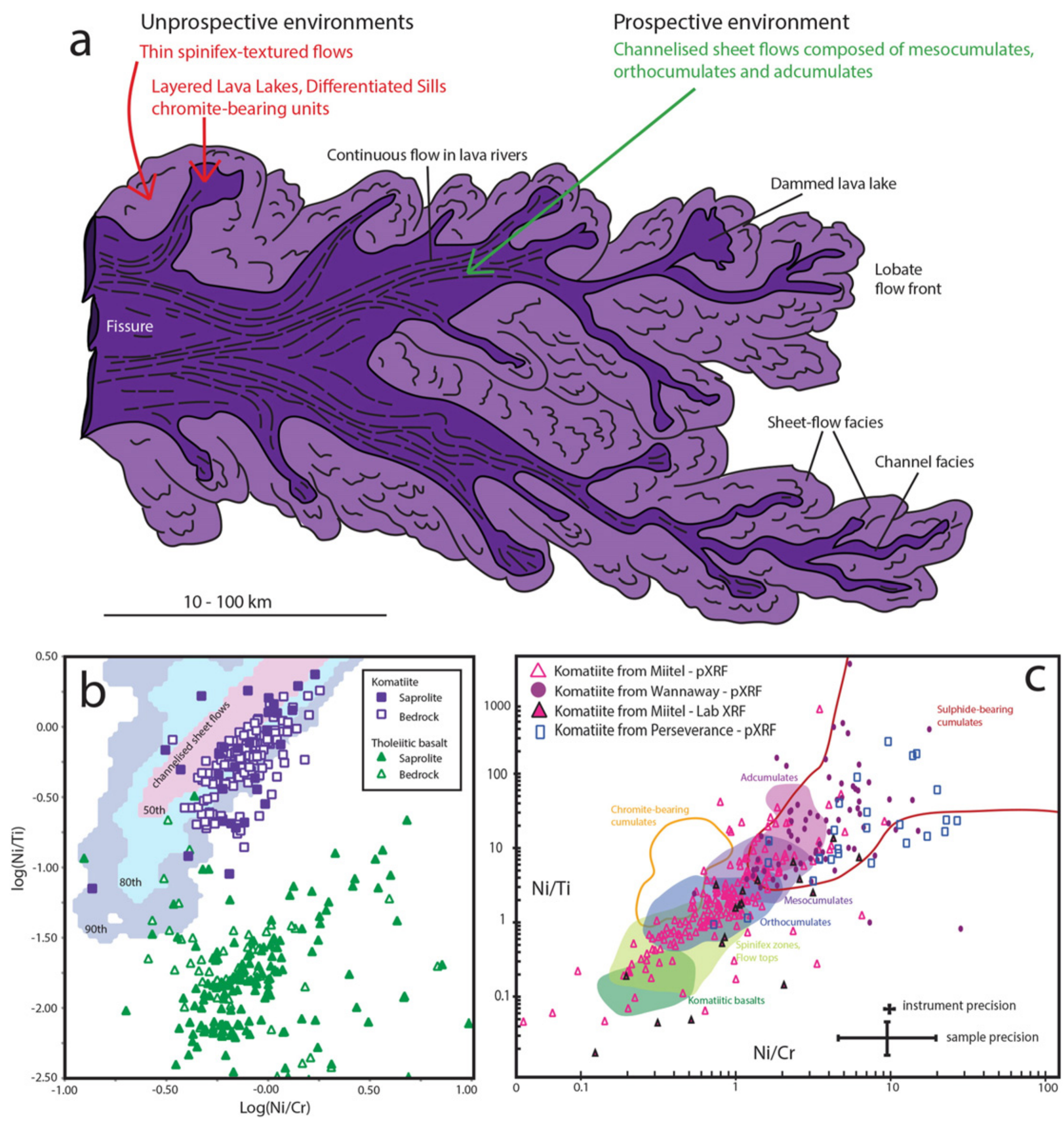


**Fig. 3.** a) Schematic illustration of a regional komatiite flow field, modified from Hill et al. (1995), b) comparison of Ni/Ti and Ni/Cr ratios between fresh bedrock and "top of fresh rock" saprolite in the Agnew area in Western Australia, data compiled by Barnes et al. (2014), and c) Plot showing the potential use of pXRF in evaluating the prospectivity of a komatiite unit using Ni/TI and Ni/Cr ratios, modified from Le Vaillant et al. (2014).

camps such as the Kambalda camp (Yilgarn craton, Western Australia) where the first nickel discoveries were made in the mid 1960's (Hronsky and Schodde, 2006). Such settings are commonly associated with craton margins, as first identified in the Cape Smith (Raglan) and Thompson komatiite belts that surround the Superior Craton (Baragar and Scoates, 1981). The Nebo Babel deposit in the West Mustgrave, Western Australia, is also a good example of a deposit that was discovered using lithospheric architectural targeting combining areas presenting evidences of major focused mantle-derived magmatism with anomalous lithospheric architecture (the boundary of the Yilgarn craton, and convergence of multiple faults including the Mundrabilla fault) (Pers. Comm. John Hronsky).

*2.2.2. Lithogeochemical tools at camp to prospect scale*

Numerous lithogeochemical exploration techniques, both predictive and detective, have been developed and successfully used over the years at the camp to prospect scale, such as:

(1) The search for evidence of crustal contamination of the magma, for instance anomalous enrichments in highly incompatible lithophile elements (Zr, Th and LREE) (Lesher et al., 2001; Barnes et al., 2004b; Fiorentini et al., 2012b), represents a predictive exploration technique used to identify prospective komatiite units. In most komatiitic systems, Zr and Ti are relatively immobile and incompatible in crystallising olivine, and Zr is more highly concentrated in crustal rocks relative to mantle melts. Hence the ratio Zr/Ti can be used as a contamination indicator, with the advantages that it is not greatly affected by alteration, metamorphism, nor fractional crystallisation (Sun and Nesbitt, 1977; Huppert and Sparks, 1985) and can be measured directly in the field using portable X-Ray fluoresence tools (pXRF) (Le Vaillant et al., 2014). Contamination signals will be detected when important amounts of fractionated (felsic) material has been assimilated by the magma (Lesher and Arndt, 1995) (e.g., Raglan camp, Cape Smith belt, Northern Quebec; Thompson nickel belt, Manitoba, Canada; Perseverance deposit, Yilgarn, Western Australia). Pervasive crustal contamination signals are observed over several km of strike in certain prospective komatiite units, such as the Black Swan komatiite complex, Yilgarn, Western Australia (Barnes et al., 2004a) and the Perseverance and Mount Keith ultramafic complexes (Barnes et al., 1988b) where komatiites were erupted on sulphide-bearing felsic substrates. Barnes and Fiorentini (2012) showed that, on the scale of greenstone belts and terranes, prospective belts tend to contain significantly higher proportions of contaminated komatiites. The mineralised portions of the Abitibi greenstone belt show distinct regional patchy anomalies in the presence of contamination signals relative to the remainder of the belt, such as elevated ratios of strongly incompatible (Th, La, Ce, Zr) to less incompatible (HREE, Ti, Nb) lithophile trace elements (Sproule et al., 2002; Barnes et al., 2007). However, in cases where komatiites were erupted onto basaltic substrates with volumetrically minor sulphidic sediments, as at Kambalda, signals of contamination can be weak and spatially limited even in well-mineralised flows (Lesher and Arndt, 1995), where the contamination seems to be limited to the flanking sheet flow facies, and abcent within the most active, central part of the the flow where the ore-forming lava has been flushed out by ongoing flow (Lesher et al., 2001; Barnes et al., 2013b). Moroever, cases of contaminated ultramafic units (e.g., Paringa Balsalts, Kambalda, (Redman and Keays, 1985) which are not mineralised and potential for false positive indications exist. However, combining evidence of crustal contamination with other observations can help identify these false positives.

(2) Channelised volcanic environments are the most prospective settings for ore deposition (Barnes and Brand, 1999; Lesher et al., 2001; Barnes et al., 2004b; Fiorentini et al., 2012b) (Fig. 3a) and can be detected with a series of geochemical criteria; this approach is useful where original rock textures are unrecognisable. For example, a Ni/Ti vs Ni/Cr diagram can be used to delineate favourable volcanic environments; Ni/Ti will correlate with original olivine content constraining the silicate nickel background and highlighting subtle sulphide-related nickel enrichment. This can be combined with the Ni/Cr ratio which gives information on the volcanic environment. Empirical observations show that prospective olivine-rich channel facies rocks tend to have higher Ni/Cr ratios than unprospective non-channel facies rocks of otherwise similar composition (Barnes, 1998), such as for example the mineralised Kambalda-style ore environments. These are characterised by high Ni and low Cr contents of sulphide-poor rocks (Barnes and Brand, 1999): around the Kambalda Dome variation of the Ni/Cr ratio has been used with some success in delineating fertile channels (Woolrich and Giorgetta, 1978). These variations in Ni, Cr and Ti contents form part of the rationale for the use of combined Ni/Cr and Ni/Ti ratios to map favourable sulphide deposition sites within komatiite flow fields (Barnes et al., 2004b), as discussed further below. However, it is now known that this approach applies only to true komatiites and not to deposits hosted within komatiitic basalt sequences, such as those in the Raglan camp, where the magmas were pervasively chromite saturated (Lesher and Stone, 1996; Lesher, 2007).These ratios can also potentially be calculated using concentrations collected directly on the field using pXRF (Fig. 3c) (Le Vaillant et al., 2014).

(3) Chalcophile element anomalies associated with magmatic sulphide extraction or accumulation, such as Ni, Cu, Co and platinum group elements (PGE), can be used as a detective exploration tool (Duke and Naldrett, 1978) usually restricted to near-deposit settings, but there are examples of more pervasive deposit scale signals. For example, in the Perseverance deposit, Agnew Wiluna greenstone belt, Western Australia, extensive depletion of nickel in olivine is observed, indicative of sulphide segregation, along with crustal contamination signals, over several km of strike (Barnes et al., 1988a). In addition, pervasive anomalies in PGEs, both positive and negative, have been identified at camp scale in the komatiitic basalts of the Raglan camp, Cape Smith belt, Northern Quebec (Barnes and Picard, 1993; Lesher et al., 2001). However, some mineralised belts such as Forrestania, Southern cross Province, Western Australia, and some regional-scale flow fields, such as the Silver Lake Member of the Kambalda Komatiite Formation of the Kalgoorlie Terrane, Western Australia, show no significant chalcophile element anomalies beyond the immediate deposit scale (Lesher et al., 2001; Barnes and Fiorentini, 2012; Barnes et al., 2013b). The dynamics and size of the komatiite flows must therefore be kept in mind when interpreting these geochemical tools. The Perseverance deposit represents an extremely dynamic and large magmatic flow, with pervasive felsic footwall assimilation and sulphide equilibration giving rise to Ni depletion in olivine in a very large volume of preserved cumulates. At Kambalda on the other hand, although the system as a whole contains comparable volumes of ore as Perseverance, mineralisation occurred within relatively low volume, strongly channelised magmatic flows with a highly localised S source. Hence, Ni depletion in olivine is only present within the immediately adjacent ore environment and does not extend much farther. Furthermore, the extent of Ni depletion depends strongly on the R factor, i.e. the mass ratio of silicate to sulphide magma that equilibrate with one another. Where R factors are relatively low, as at Perseverance, ore tenors are lower and Ni depletion in silicate magma and olivine correspondingly greater, relative to high R factor deposits with high Ni tenor and only minor Ni depletion (Barnes et al., 2013a).

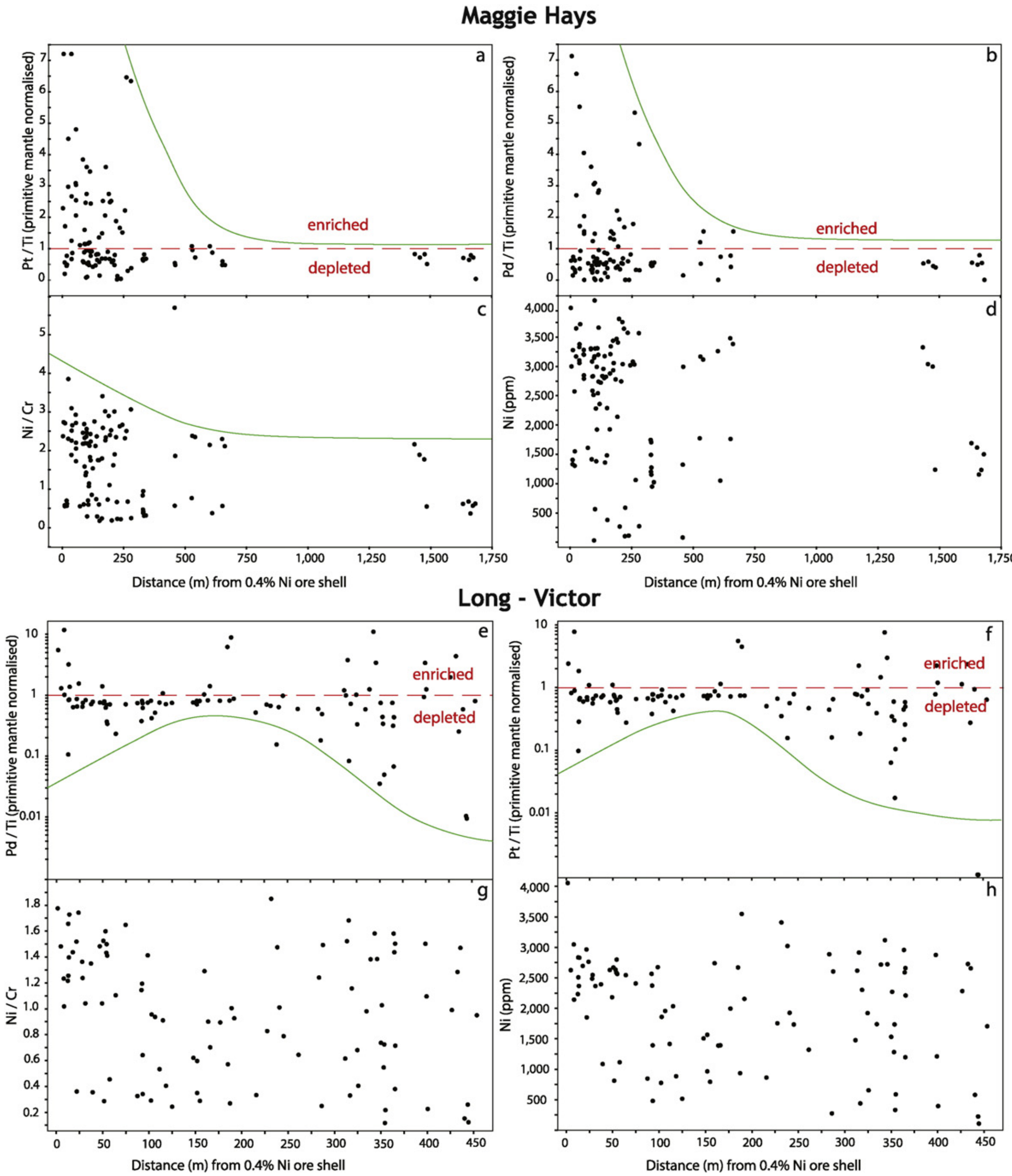


**Fig. 4.** Comparison at Maggie Hays and Long Victor of the spatial extend between Ni/Cr and PGE halos. Modified from Barnes et al. (2013b).

(4) At the camp to prospect scale, sulphur isotopes can represent a very informative tool both for prediction and detection. Sulphur isotope data can help identify favourable tectonic settings for interaction of komatiite flows with extensive S-rich source rocks by testing crustal assimilation model (Lesher and Groves, 1986a), and identifying the potential for multiple crustal sulphur reservoirs that could contribute to ore genesis (Fiorentini et al., 2012a).

### 2.2.3. Detective techniques at deposit scale

As the scale of exploration closes in to deposit scale, the availability of detection techniques increases (McCuaig et al., 2010). Over the years, several detection techniques have been developed for komatiite-hosted Ni-Cu-(PGE) deposits. However, their efficiency is still limited, mainly due to the small size and ribbon-like geometry of these Ni-Cu-(PGE) sulphide ore bodies (Fig. 1). The main available exploration tools that have been developed for the use at the deposit scale are as follows:

(1) The detection of anomalous whole-rock enrichment and/or depletion of chalcophile elements (Ni, Cu, Co, PGEs) in komatiite units as an indication of sulphide segregation and accumulation (Lesher et al., 2001; Barnes et al., 2004b; Fiorentini et al., 2010; Fiorentini et al., 2011). At the Long Victor (Kambalda) and Maggie Hays nickel-sulphide deposits, Western Australia, Barnes et al. (2013b) and Heggie et al. (2012) observed subtle PGE enrichments (and depletions, in the Long-Victor example) in host komatiite units extending up to 400 m away from

mineralisation. Normalisation to an incompatible minor element, such as Ti, is required to compensate for the variability introduced by olivine fractionation or accumulation. The study of nickel contents in olivine also represents a useful tool (Duke and Naldrett, 1978; Duke, 1979)that has nonetheless limitations, owing to 1) the relatively rare preservation of fresh olivine in komatiites, which are almost universally pervasively altered, and to 2) the lower sensitivity of Ni relative to PGEs to sulphide-related depletion due to its much lower partition coefficient (Duke and Naldrett, 1978; Duke, 1979). However, PGE-based techniques require expensive high-precision analyses.

(2) A similar limitation applies to the use of Ni/Cr ratios, which can delineate ore-related channels (Barnes and Brand, 1999), through picking up Ni enrichment directly and also by discriminating cumulates formed in high-temperature lava channels. Olivine cumulates in ore-bearing channels (in true komatiites, although not in komatiitic basalts) tend to have higher Ni/Cr even in samples that are not mineralised. This is for two reasons: the magmas tend to be hotter, and therefore less likely to be chromite-saturated; and even when the magmas were chromite-saturated, as they were at Mt. Keith and most of Perseverance (Barnes et al., 2011), chromite crystallisation seems to be supressed in high-flux channel settings, especially when there is sulphide present as well (Barnes, 1998). For example Ni/Cr was used to image ore shoots in the Kambalda area, Western Australia (Woolrich and Giorgetta, 1978). However, the Ni/Cr ratio is not significantly more effective than nickel anomalies alone (Barnes et al., 2013b), as discussed below in the section comparing various exploration tools.

Barnes et al. (2013b) and Heggie et al. (2012) compared the effectiveness of variations in Ni/Cr, nickel alone and Pt/Ti as vectors towards ore bodies within cumulate-rich komatiitic complexes, and results are summarised in Fig. 4. Both in an extrusive channelised flow complex (Long-Victor at Kambalda) and in a subvolcanic dunite-bearing intrusive conduit (Maggie Hays), variations in the ratio of Pt/Ti and Pd/Ti can be detected in essentially sulphide-free rock some 400 m away from detectable ore. In the Kambalda case, this takes the form both of PGE depletion in flanking flow tops, owing to batch equilibration of the magma with the sulphide liquid within the flows, of which the central part (channel) is then flushed by PGE-undepleted melt, and PGE enrichment close to the ores owing to the presence of otherwise undetectable proportions of highly PGE-enriched sulphide. Both the depleted and enriched signals extend up to 450 m away from the 0.4% Ni grade shell (the effective limit of detectable disseminated sulphides) and are much clearer than the very subtle variation in Ni/Cr between channel and flank facies, which is mainly evident in minimum values at the bottom of the envelope of variability across and away from the channel (Fig. 4a,b). Using the ratio Ni/Cr in this case appears to confer no advantage over using the elemental nickel abundance by itself, although Ni/Cr can be used in mildly weathered or extensively altered rocks where absolute whole-rock Ni and Cr may have been diluted or enhanced. At Maggie Hays, a subtle increase in Ni/Cr and a much more pronounced increase in Pt/Ti and Pd/Ti appear at about 300 m distance from the disseminated sulphide shell, but the Pt/Ti and Pd/Ti define particularly clear vectors of systematic increase towards ore. Values above 1 (mantle normalised value) appear up to 650 m away with a systematically increasing trend developed within the inner 250 m (Fig. 4).

(3) The detection of ruthenium depletion in chromite grains, obtained by laser-ablation ICP-MS analyses of chromite grains either in situ or from a mineral separate, shown as characteristic of mineralised komatiites by Locmelis et al. (2013), can potentially be used to discriminate between mineralised and barren komatiite flows (Fiorentini et al., 2008; Locmelis et al., 2011; Locmelis et al., 2013). Care must be taken to compare rocks which have cooled at similar rates, as cooling rate seems to have an effect on Iridium-group PGE (IPGE) concentrations of chromites (Pagé and Barnes, 2016).

(4) Finally, the evaluation of the thickness of sediment units at basal komatiite contacts could potentially be used for exploration, as a tight mutually exclusive relationship between the distribution of sulphidic sediments and Ni-Cu-(PGE) sulphide ores has been demonstrated at Kambalda (Bavinton, 1981; Paterson, 1984; Lesher and Groves, 1986a), and was used extensively as an exploration guide during the early delineation of the orebodies (Gresham and Loftus Hill, 1981).

Most of the exploration tools described above do not extend over 50 to 100 m away from massive sulphides, mainly because of the dynamic nature of the ore-forming channels and resulting flushing out of early ore-forming magma during the later stages of the eruption. Moreover, these techniques rely on the present geometry being similar to the one upon emplacement, whereas komatiite-hosted Ni-Cu-(PGE) systems have undergone polyphase deformation (e.g., Duuring et al., 2007; Layton-Matthews et al., 2007; Duuring et al., 2010; Bleeker et al., 2012), rendering these detection tools ineffective.

Finally, geophysical methods are of great importance to identify prospective areas and define drilling targets, particularly when integrated with other datasets. Electromagnetic (EM) techniques are, in certain environments, a very efficient tool to detect massive nickel-sulphide ore bodies, particularly in low conductive backgrounds. For example, the recently discovered Nova deposit in the Fraser Range Domain, Western Australia, was first intersected by a drill hole meant to test a large and strong EM anomaly (Bennett et al., 2014). The distance of detection for down-hole EM (DHEM), which is one of the standard techniques, mainly depends on the shape and the size of the target, and varies between 0.5 to 1.5 times the smaller dimensions of the ore body, therefore generally extending 50 to 150 m from massive sulphides (pers. com. Bill Amann – Newexco Services Pty Ltd., Lisa Vella – Southern Geoscience Consultants, John Hronsky – Western Mining Services (Peters, 2006), making it a highly effective tool to follow brownfield ore body extensions. However, the following characteristics of komatiite-hosted Ni-Cu-(PGE) deposits give rise to several limitations for geophysical methods: ore bodies are often small and deep seated, barren sedimentary and exhalative sulphide units are commonly in close spatial association with the ore bodies, and in Australia particularly, large amounts of saline groundwater and salt are present in the cover, challenging EM interpretations (González-Álvarez et al., 2016). Finally, the main drawback of DHEM is the high false positive rate due to EM anomalies associated with barren sulphidic or graphitic metasediments, which makes it difficult to discriminate nickel-rich from barren sulphide bodies (Peters, 2006).

All exploration tools described above are combined in Table 1. To summarise, type I komatiite-hosted Ni-Cu-(PGE) deposits remain very difficult exploration targets. Their general location can be reasonably well predicted thanks to an extensive knowledge of their genetic processes, but to this date no completely effective detection technique (geochemical or geophysical) allows explorers to locate them and identify them from sparse drilling. Consequently in Western Australia for example, the rate of discovery of this deposit style has slowed down dramatically since the initial surge of exploration success between 1966 and 1973 (Hronsky and Schodde, 2006). Undiscovered deposits are highly likely to exist at depth, even in mature well-explored terranes, and in some cases are deformed, altered and offset from their original position. A new approach is needed to aid exploration in brownfields terranes by enlarging the detectable footprints of undiscovered deposits. Secondary hydrothermal haloes surrounding primary magmatic deposits have potential to be useful signals and we consider these next.

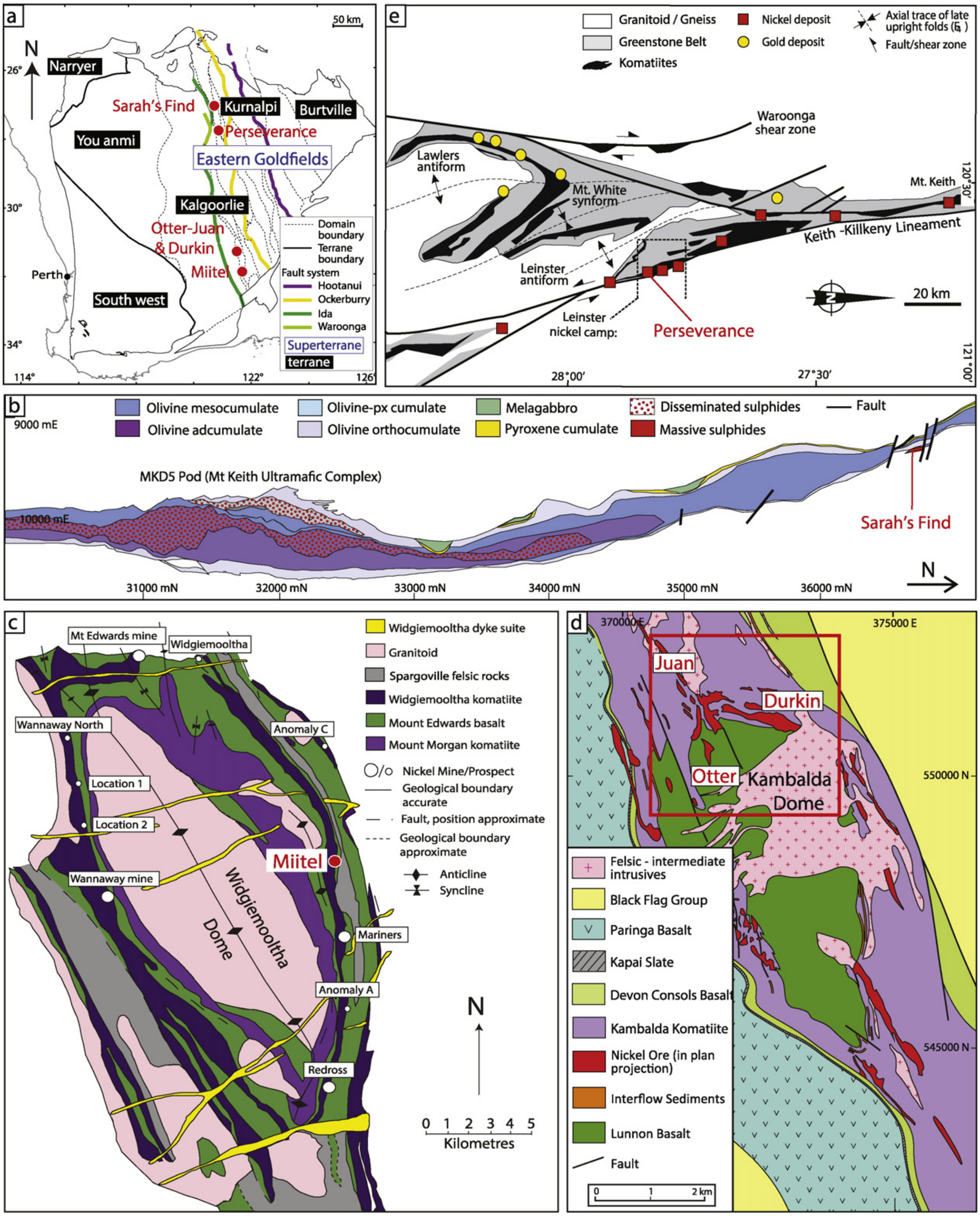


**Fig. 5.** Geological maps locating the various case studies used within the project on hydrothermal haloes. a) Simplified geological map of the Yilgarn Craton showing the location of the case studies, modified from Cassidy et al. (2006). b) Location of the Sarah's Find prospect on a detailed geology of the Mount Keith ultramafic complex (from Barnes et al. (2011); Fiorentini et al. (2007) after Rosengren et al. (2007)). c) Geological map of the Widgiemooltha Dome area showing existing Ni-Cu-(PGE) mines and prospects (adapted and modified after Seat et al. (2004) and McQueen (1981), originally modified after Willett et al. (1978)). d) Location map of Kambalda dome modified from Barnes (2006a) e) Regional map of the Perseverance area, modified from Hill et al. (1995); Trofimovs et al. (2003), and Duuring et al. (2010).

## 3. Hydrothermal remobilisation and geochemical haloes

Most magmatic Ni-Cu-(PGE) deposits have been altered and modified to some degree as a result of interaction with post-magmatic (or syn-magmatic) hydrothermal and metamorphic fluids. The interaction between these fluids and massive nickel-sulphide bodies has the potential to create a relatively large dispersive footprint with specific mineralogical and lithogeochemical characteristics.

### 3.1. Review of recent studies

The few previous studies looking at hydrothermal haloes around magmatic Ni-Cu-(PGE) deposits show promising results. At the Barnet property, part of the Sudbury Cu-Ni-(PGE) camp (Canada), wide scale mobility of nickel in hydrothermal solution in the footwall of the deposit has been highlighted by the presence of elevated concentrations of nickel in secondary amphiboles (Hanley and Bray, 2009). This significant mobility (up to 700 m) was probably facilitated in that system by extreme impact-related fracture permeability. Another study by Layton-Matthews et al. (2007) on Ni-Cu-(PGE) deposits of the Thompson Nickel Belt highlights enrichment in Ni, Au, Pd and Cu within sedimentary sulphide units adjacent to the nickel-sulphide deposits. At Thompson, this enrichment is interpreted as being either created during the mobilisation of fluids generated by the metamorphism of both the ore zones and their host rocks (Bleeker, 1990) or via syn-magmatic diffusion of metals (Burnham et al., 2003). Finally, according to a study by Barrie et al. (2007), hydrothermal haloes are present around the River Valley, Fergusson Lake and Kabanga deposits. Their results show subtle anomalies in combined metal and/or transition elements in country rocks, extending up to several hundred metres away from massive sulphides, but are difficult to evaluate owing to a lack of control background data from unmineralised environments.

In addition, there are an increasing number of studies on hydrothermal nickel and/or PGE accumulations. In the Sudbury camp, the low-sulphide, Pt- and Pd-rich haloes (150 m away from massive sulphides) around vein-type Ni-Cu-PGE ores in the footwall of the Sudbury Igneous complex (SIC), have been interpreted as the result of remobilisation of PGE (mainly Pt and Pd) from differentiated sulphide liquids by late magmatic-deuteric and/or hydrothermal fluids (Farrow and Watkinson, 1996; Molnár et al., 1999; Molnar and Watkinson, 2001; Molnár et al., 2001; Hanley and Mungall, 2003; Mossman et al., 2003; Hanley et al., 2005; Péntek et al., 2008; Hanley et al., 2011; Péntek et al., 2011; Molnár, 2013; Péntek et al., 2013; Tuba et al., 2014).

Finally, recent studies indicate the possibility of remobilisation of large amounts of nickel from sulphide sources, on a scale of hundreds of metres up to kilometres in some specific cases (González-Álvarez et al., 2010; González-Álvarez et al., 2013a; González-Álvarez et al., 2013b; Keays and Jowitt, 2013; Pirajno and González-Álvarez, 2013), and some hydrothermal PGE-(Au) deposits have also been reported (Dillon-Leitch et al., 1986; Nyman et al., 1990; Olivo and Theyer, 2004; De Almeida et al., 2007; Bursztyn and Olivo, 2010). All these results, combined with recent studies on the behaviour of Ni, Pd and Pt in hydrothermal fluids (Barnes and Liu, 2012; Yuan et al., 2015; Le Vaillant et al., 2016), show that, despite the widespread belief that Ni and PGE are extremely immobile elements under most circumstances, specific fluids and geological contexts have the capacity to remobilise nickel and PGE from a massive sulphide source and potentially form hydrothermal haloes useful for exploration targeting.

### 3.2. Recent studies of komatiite-hosted systems

As part of a large study on hydrothermal geochemical haloes around komatiite-hosted Ni-Cu-(PGE) deposits (Le Vaillant, 2014), five deposits were studied in detail: Miitel, Sarah's Find, Perseverance, Otter-Juan and Durkin. These deposits are located in the Archean Norseman-Wiluna greenstone belt, which is the supracrustal component of the Kalgoorlie Terrane, within the Eastern Goldfields Superterrane (Cassidy et al., 2006), Yilgarn craton, Western Australia (Fig. 5a). The same methodology was applied in these five case studies, which carried out geochemical analyses of samples located in footwall lithologies along major fluid pathways cross cutting the mineralisation. Nickel-As-PGE (Pd, Pt) haloes were observed and characterised for two deposits (Miitel and

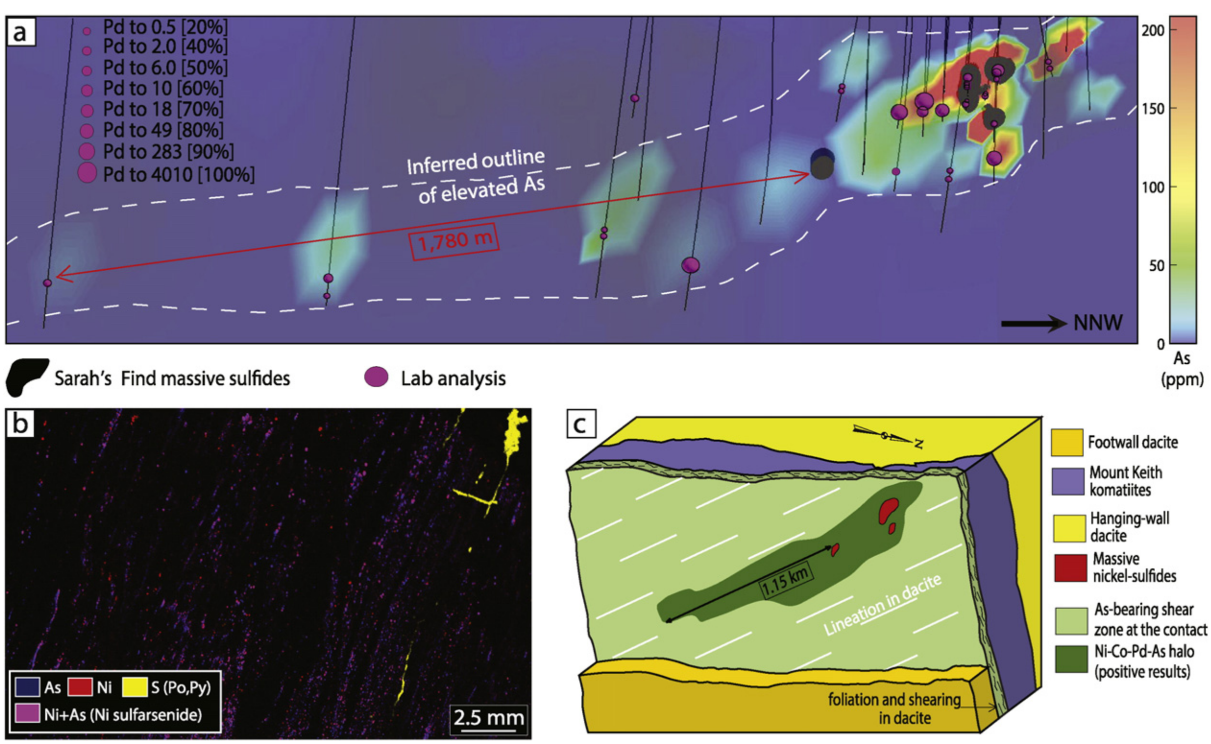


**Fig. 6.** Summary of results from the study of the Sarah's Find deposit. a) 3D visualisation of concentrations in Pd of all analysed samples, combined with a colour representation of the arsenic concentrations along the footwall contact between the Mount Keith komatiites and the Mount Keith dacite. b) micro-XRF map of one of the sample containing nickel arsenides within the foliation in the dacite footwall. c) Interpretative block model of the geochemical halo observed around the Sarah's Find ore body.
Modified from Le Vaillant et al. (2015b).

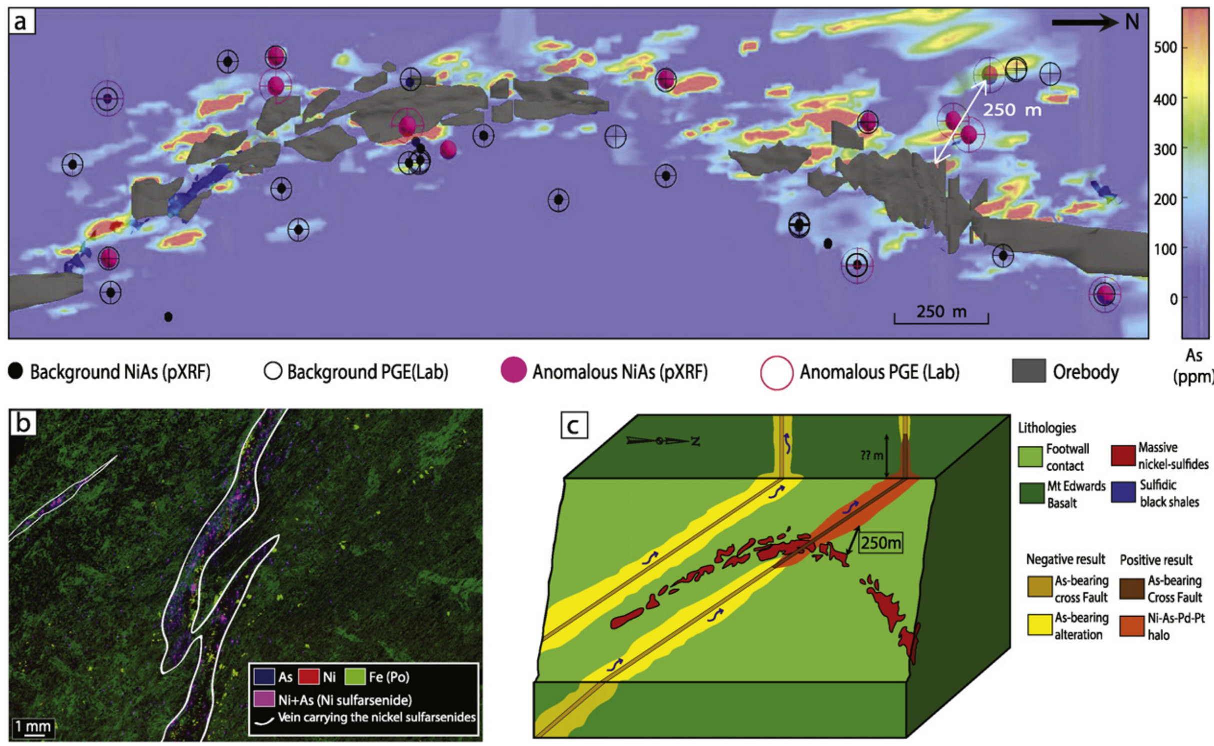


**Fig. 7.** Summary of results from the study of the Miitel deposit. a) Perspective view from gOcad® of a long section through the 3D model of the Miitel deposit. This image combines: 1) distribution of the arsenic in ppm at the contact between the basalt and the komatiites (model derived using Leapfrog®), 2) location of pXRF analyses showing anomalously high Ni and As concentrations, and 3) location of laboratory PGE analyses highlighting samples enriched in PGE. b) False colour element concentration map (As blue, Ni red, Fe green), of samples DRD918-358.6 which contains nickel arsenides within small hydrothermal quartz and/or carbonate veins cross cutting the Mount Edwards footwall basalt. This map was produced using the data collected with the Maia detector array on the X-ray fluorescence microscopy beamline, at the Australian Synchrotron in Melbourne. c) 3D block model of the Miitel system showing the possible application of the Ni-As-Pd geochemical halo to exploration targeting for nickel sulphides.
Modified from Le Vaillant et al. (2015a).

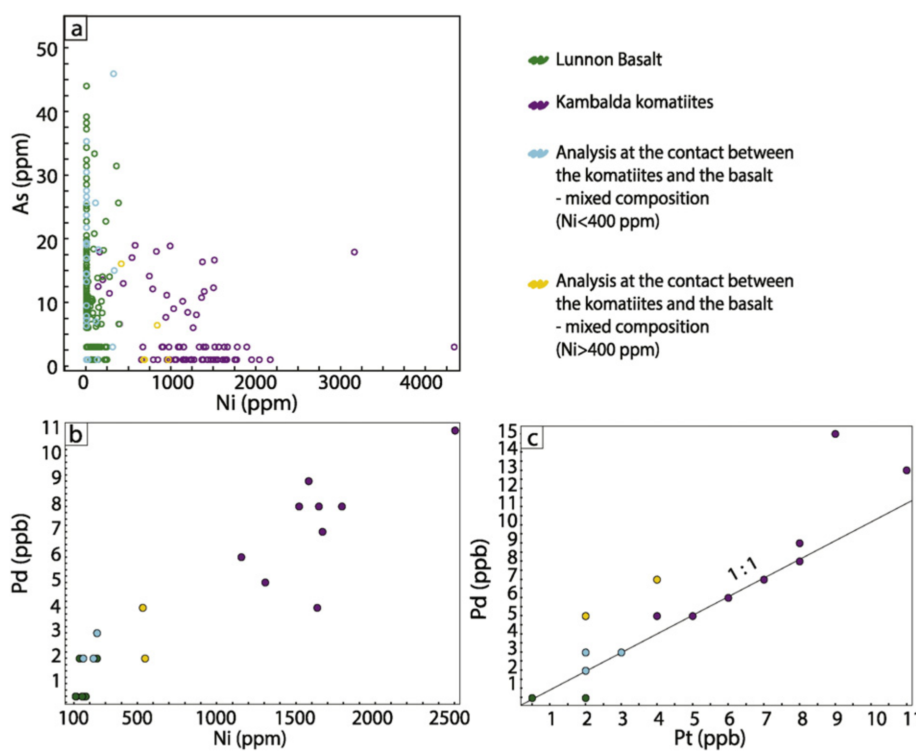


**Fig. 8.** Results from the study of Otter Juan and Durkin. Portable XRF analyses results (A) and laboratory analyses results (B and C) from samples collected along fluid pathways cross cutting the ore.
Modified from Le Vaillant (2014).

Sarah's Find), whereas three others did not show evidence of hydrothermal remobilisation (Perseverance, Otter-Juan and Durkin).

### 3.3. The Sarah's Find deposit

The Sarah's Find deposit is located 4.5 km north of the Mount Keith deposit in the Agnew-Wiluna greenstone belt (Fig. 5b) (Fiorentini et al., 2007). It is composed of very small lenses or stringers of massive sulphides at the basal contact between the Mount Keith komatiite and the Mount Keith dacite footwall. At Sarah's Find, a Ni-Co-Pd-As geochemical halo was observed around the massive sulphides (Le Vaillant et al., 2015b). This halo is interpreted as the result of combined physical (solid state) and hydrothermal remobilisation of Ni, Co and PGEs (Pd, Pt) from the massive sulphides. Physical remobilisation is observed up to 100–150 m away from the massive sulphides, within the footwall dacite, along the contact with the komatiitic host rock (Mount Keith Ultramafic Unit), parallel to the direction of shearing. Ni, Co and PGE (mainly Pd, and to a lesser degree Pt) are also interpreted as being hydrothermally remobilised by syn-deformation As-rich hydrothermal fluids, and re-deposited in an even larger halo than the one produced by physical remobilisation, prevalently along the direction of shearing (Fig. 6). These As-rich fluids collected Ni, Co and Pd from the Sarah's Find massive sulphides and re-deposited them as nickel sulfarsenides within the sheared footwall dacite, along the dominant NNW striking foliation, creating this geochemical halo extending along the direction of shearing up to 1780 m away from the massive sulphides.

Two types of nickel arsenides associated with this physical and hydrothermal halo were observed: Type (1), which is interpreted as forming by hydrothermal remobilisation of Ni-Co-Pt-Pd from the massive sulphides by As-rich fluids (possibly also containing small amounts of Au that was not incorporated/deposited) re-depositing them as Co-rich gersdorffite (NiAsS) within the foliation. These gersdorffite grains contain small PGE concentrations (0.1–3.5 ppm Pt and 0.8–21.4 ppm Pd in average, with other PGEs below 0.2 ppm) and Au (averages between 1.6 and 62 ppm). Two possible interpretations exist for type (2) which is composed of Ni-rich gersdorffites containing high PGE concentrations (0.1–1.1 ppm Pt, 12–356 ppm Pd in average) but no Au (less than 1.8 ppm in average). These Ni-rich gersdorffite grains could have either been present within the sulphides, where they formed following As-enrichment of the sulphide melt by crustal assimilation of the komatiitic magma upon emplacement (i.e., 'magmatic origin'), and then be sheared along with sulphides during the deformation event, or they could have formed by alteration of the sheared sulphides by As-rich hydrothermal fluids (i.e., hydrothermal origin). However, if the arsenides from type (2) were magmatic, they would display a more 'magmatic' composition with elevated concentrations in iridium series platinum group elements (IPGEs) (Lesher and Keays, 1984, 2002; Godel et al., 2012), which is not the case.

### 3.4. The Miitel deposit

Miitel is an Archean komatiite-hosted Ni-Cu-(PGE) deposit located on the eastern flank of the Widgiemooltha Dome (Seat et al., 2004) within the Kalgoorlie Terrane (Swager, 1997) (Fig. 5c). The Miitel ore bodies are located at the basal contact between the Widgiemooltha komatiites and the Mount Edwards basalt; the whole area has undergone upper greenschist to lower amphibolite facies metamorphism (McQueen, 1981, 1987; Hayward, 1988; Barnes and Hill, 2000; Le Vaillant et al., 2015a). Le Vaillant et al. (2015a) documented a cryptic Ni-As-Pd-Pt geochemical halo around the ore body, formed by the late magmatic or metamorphic circulation of arsenic-rich hydrothermal fluids (Fig. 7). These arsenic-rich fluids were prevalently flowing upwards, mainly along the footwall contact between the komatiitic host rock and the footwall basalt, and along late SSW shallow-dipping cross-cutting splay structures. These hydrothermal fluids collected Ni and PGEs, mainly Pd and Pt, from the massive nickel sulphides, transported them, and re-deposited them within mm to cm wide quartz and/or carbonate veins close to the footwall contact (Fig. 7b). The geochemical halo produced by the hydrothermal circulation of arsenic-rich fluids extends along the basal contact at least 250 m away from the ore. In addition, it is inferred that the larger spread of arsenic-rich metasomatism in rocks surrounding the deposit (As >100 ppm in whole-rock data), especially along the splay structures outside the limit of drilling availability, could reflect an even wider Ni-As-PGE halo.

### 3.5. The Otter-Juan and Durkin deposits

The Otter-Juan and Durkin komatiite-hosted Ni-Cu-(PGE) deposits are located on the N-NE side of the Kambalda Dome (Fig. 5d). The geology of the Otter-Juan and Durkin Ni-Cu-(PGE) deposits is similar to that of the Miitel deposit, with massive sulphides located at the basal contact between komatiites (the Lower Silver Lake komatiites) and a thick homogeneous basalt (Lunnon Basalt Formation) (Gresham and Loftus Hill, 1981). The volcanic sequence of the Kambalda Dome has undergone significant structural modifications with important folding and faulting and, similarly to the Miitel deposit, upper greenschist facies regional metamorphism (Barrett et al., 1977; Bavinton, 1981). No hydrothermal haloes such as the cryptic one observed at Miitel were detected around Otter-Juan and Durkin; none of the analyses collected highlighted anomalously elevated values in Ni and PGE (Fig. 8a). Moreover, Pd and Pt values obtained for all the analyses show a positive correlation ($R_{Pd/Pt} = 0.8$, $R_{Pd/Ni} = 0.8$) (Fig. 8b, c). Since Pd and Pt behave differently

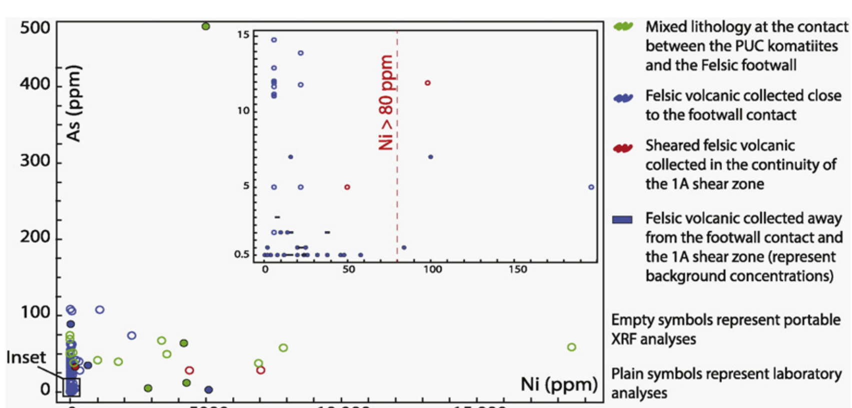


**Fig. 9.** Portable and laboratory analyses results from samples collected along fluid pathways cross cutting the Perseverance ore body. Modified from Le Vaillant (2014).

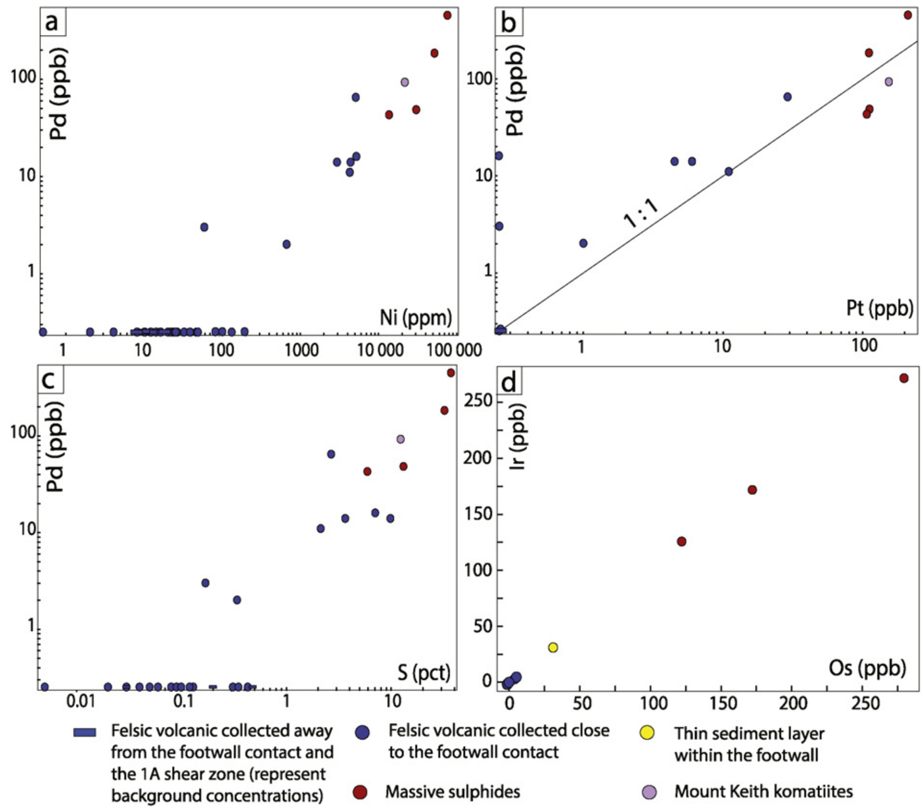


**Fig. 10.** Results of Ni-sulphide fire assay ICP-MS analyses obtained on samples collected along fluid pathways cross cutting the Perseverance ore body. Modified from Le Vaillant (2014).

within hydrothermal fluids (Barnes and Liu, 2012), a lack of decoupling between their concentrations is a good indicator that they have not been significantly mobilised by hydrothermal fluids. Moreover, it is important to note that As concentrations within the collected samples are also very low, and that the deposits have apparently not interacted with As-rich fluids (Le Vaillant, 2014).

### *3.6. The Perseverance deposit*

The Perseverance deposit, previously known as Agnew (Barnes et al., 1988a), is one of the largest known komatiite-hosted Ni-Cu-(PGE) deposits (Barnes et al., 2011; Perring, 2015a, 2015b) containing at least 1.2 Mt Ni. It is located in the southern part of the Agnew-Wiluna greenstone belt, which in the area comprises a narrow package of deformed and metamorphosed supracrustal rocks, bordered by granitic gneiss terrains (Eisenlohr, 1988; Duuring et al., 2010), and delimitated by the Waroona shear zone to the West (Platt et al., 1978) and the Mt. Keith-Kilkenny tectonic zone to the East (Eisenlohr, 1988) (Fig. 5e). The geological setting of the Perseverance deposit is comparable to that of the Sarah's Find deposit where massive sulphide lenses are present at the contact between komatiites and a felsic footwall.

The Perseverance deposit is composed of both matrix and massive sulphides hosted by the Perseverance ultramafic complex, enclosed within volcanic sediments (Duuring et al., 2010). The footwall rocks are composed of fine grained, schistose, biotite-rich volcanic-sedimentary rocks overlain by fragmental-textured rhyodacite and plagioclase-quartz-phenocryst-rich rhyodacite (1 to 80 m thick), which are in contact with the Perseverance ultramafic complex and were the focus of this study. The Perseverance ultramafic complex is a 7 km long, 800 m thick unit composed of komatiitic olivine meso- to adcumulates with sulphides located at the basal contact between the Perseverance ultramafic complex and the rhyodacite footwall. The Perseverance area has undergone a high strain polyphase deformation history at low to mid-amphibolite facies metamorphism (Binns and Groves, 1976; Gole et al., 1987; Duuring et al., 2010). In this framework, one of its longest ore shoots, the 1 A ore body composed of variably mylonitised breccia ore, extends away from the komatiite complex in the isoclinal N-NW hinge of a synform. This deformation event, which is related to a 20 m wide mylonite zone in the footwall unit, was produced during a regional D3 event (Perring, 2015a, 2015b). The 1 A ore shoot contains slivers of sheared ultramafic rocks and can be traced up to 600 m to the north of the main ultramafic lens (Barnes et al., 1988a).

In the study of hydrothermal haloes at Perseverance, Le Vaillant (2014) focused on samples of the footwall rhyodacite collected close to the contact with the Perseverance ultramafic complex or within the extension of the 1 A shear zone. No geochemical halo could be detected surrounding the mineralisation. Within the analysed samples, only few contained anomalous nickel concentrations (see Fig. 11), which could be explained by the presence of mechanically remobilised sulphides from the massive sulphides within the 1 A shear zone (Fig. 9). Moreover, PGE values within the felsic footwall were also low, and showed strong correlations with one another ($R_{Pd/Pt} = 0.8$ and $R_{Ni/Pd} = 0.9$). Finally, when combined with results from the massive sulphides, Pd, Pt, Ni and S show a tight, positive correlation (Fig. 10a, b, c); a weaker but still observable positive correlation between the various IPGEs also exists, as shown in Fig. 10d (Le Vaillant, 2014).

The spatial distribution of arsenic concentrations at Perseverance is more complex than at Otter-Juan and Durkin. Elevated As values are present within some areas of the massive sulphides, mainly due to the presence of gersdorffite, and extend within sheared parts of the ore body such as the 1 A ore shoot (Diragitch, 2014). Elevated values can also be found in the matrix and disseminated ores within the Perseverance ultramafic complex. However, arsenic values are consistently low to below detection limit within the rhyodacite footwall, and even in the continuity of the 1 A shear zone away from physically remobilised sulphides.

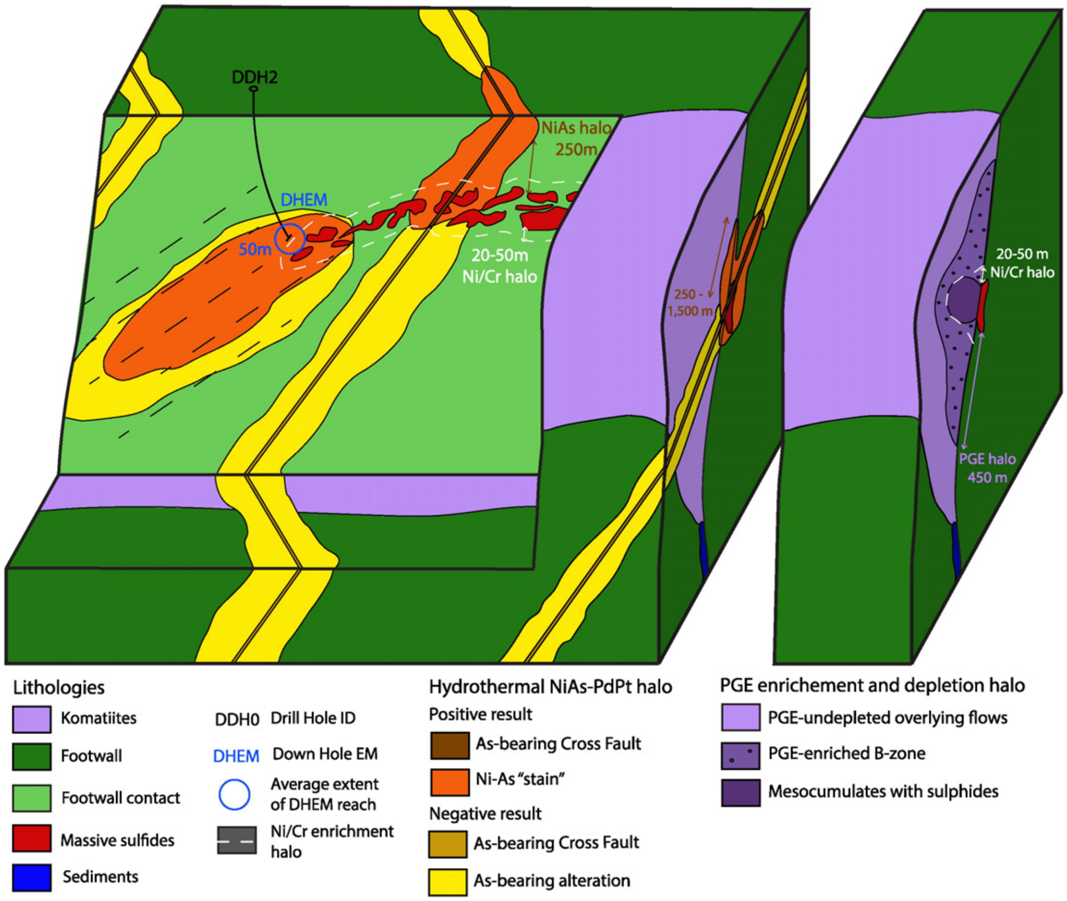


**Fig. 11.** 3D block model compiling and comparing various spatial exploration tools at the deposit scale.

### *3.7. Conclusion and short discussion comparing results of these studies of hydrothermal haloes around different komatiite-hosted nickel sulphide-deposits*

The studies of the Otter–Juan, Durkin and Perseverance ore bodies did not show evidence of hydrothermal haloes, even though these deposits have undergone several phases of deformation and alteration, similarly to the Miitel and the Sarah's find deposit, which do have large hydrothermal haloes. These systems did not attain the necessary conditions allowing Ni and PGEs to be either incorporated in hydrothermal fluids and mobilised or even just re-deposited. Results obtained for the various "hydrothermal halo" case studies are compared in Table 2.

The Miitel deposit and the Otter-Juan and Durkin ore shoots are directly comparable case studies as they are both Kambalda-style type 1 deposits (Lesher, 1989; Hill and Gole, 1990) hosted at the basal contact between channelised komatiites and footwall basalts; in addition, all these komatiite localities have undergone similar metamorphic grades and alteration. The main difference between these two localities is the absence of arsenic metasomatism in the North Eastern part of the Kambalda Dome, where the Durkin and Otter-Juan deposits are located (maximum of 60 ppm As measured, with most values below detection limits), compared to the widespread arsenic overprint observed within the Miitel deposit area (values ranging from 35 to 2405 ppm As). At Miitel, arsenic seems to have played the critical role of a ligand in remobilising Ni and PGEs and redepositing them as nickel arsenides within a geochemical halo (Le Vaillant et al., 2015a). These late, arsenic-rich fluids are commonly related to orogenic gold events (Eilu and Groves, 2001). If the arsenic-rich fluids that circulated through the Miitel deposit are similar to the arsenic-rich fluids related to many orogenic gold deposits in the Widgiemooltha Dome area, their composition coupled with the local redox conditions, might be favourable to remobilisation transport and re-deposition of Ni, Pd and Pt from sulphides.

The Sarah's Find and Perseverance deposits are also comparable case studies, with massive sulphides located at the basal contact between komatiites and felsic volcanic footwalls, as well as extending along a major shear zone (footwall contact at Sarah's Find and 1 A shear zone at Perseverance). The 1 A shear zone and the Felsic Nose ore shoots, which were the focus of the study at Perseverance, have clearly been deformed and elongated along a major shear zone, where hydrothermal fluids are likely to have circulated. However, no evidence of chemical re-mobilisation of sulphides is present. Observations on footwall rhyodacite only yielded very few anomalous nickel concentrations, interpreted as being generated by the presence of either mechanically sheared sulphides along the 1 A shear zone into the rhyodacite, or tectonically interfoliated rhyodacite and komatiites (Le Vaillant, 2014), and trends in the PGE and nickel concentrations support the hypothesis of mechanical over hydrothermal re-mobilisation of these metals. Relative abundances of Ni and PGEs in the 1 A ore shoot are identical to those in the primary massive sulphides preserving original magmatic contacts (Barnes et al., 1988b), Pd and Pt show a positive correlation with a consistent ratio close to 1:1, a positive correlation between S contents and Ni-PGE concentrations is observed; and finally IPGEs are present within the samples containing sulphides (average concentrations in disseminated and massive sulphides: 192 ppb Ir, 193 ppb Os, 509 ppb Ru and 134 ppb Ru) and show a tight correlation between one another.

If the PGEs had been hydrothermally remobilised, a decoupling between Pd, Pt and the less mobile IPGEs (Ir, Os, Ru, Rh) would be expected, as well as a decoupling between Pd and Pt, considering that Pd is one order of magnitude more soluble than Pt (Wood, 2002; Hanley, 2005;

**Table 2**
General information and summary of the results obtained during the study of hydrothermal haloes around various Australian komatiite-hosted nickel sulphide deposits.

| Deposit | Site stage | Greenstone belt | Location | Contained commodity (kt) and grade (Ni) | Footwall type | Arsenic metasomatism | Hydrothermal halo | References |
|---|---|---|---|---|---|---|---|---|
| Miitel | Operating | Norseman Wiluna | 42.0 km South of Kambalda X: 371457 Y: 6504801 | 1.56 kt at 2.9% Ni | Mafic - thick tholeitic basalt, the Mount Edwards basalt | Yes, secondary enrichment in arsenic present and widespread | Ni-As-PGE hydrothermal halo extending up to 250 m away from massive sulphide mineralisation | Cairns et al. (2003), Le Vaillant et al. (2015a) |
| Perseverance | Care and maintenance | Agnew Wiluna | 11.4 km North of Leinster X: 273997 Y: 6920833 | 276 kt at 2.3% Ni | Felsic - fine grained, schistose, biotite-rich volcanic-sedimentary rocks overlain by fragmental –textured rhyodacite and plagioclase-quartz phenocrysts rich rhyodacite | Elevated arsenic concentrations in some areas of the massive sulphides and areas where they have been mechanically remobilised - not widespread | No hydrothermal halo observed surrounding the massive sulphides (only mechanical remobilisation of the sulphides) | Martin and Allchurch (1975), Binns and Groves (1976), Platt et al. (1978), Billington (1984), Gole et al. (1987), Barnes et al. (1988a, 1988b), Barnes (2006a, 2006b), Duuring et al. (2007, 2010), Barnes et al. (2011); Le Vaillant (2014) |
| Sarah's find | Prospect | Agnew Wiluna | Northern part of th Mount Keith Domain X: 255200 Y: 6990650 | Non economic | Felsic - dacite | Yes, secondary enrichment in arsenic present and widespread | Ni-As-PGE hydrothermal halo observed extending up to 1780 m away from massive sulphide mineralisation (Le Vaillant et al., 2015b) | Burt and Sheppy (1975), Dowling and Hill (1990), Hill et al. (1995), Rosengren et al. (2005, 2007), Fiorentini et al. (2007), Le Vaillant et al. (2015b); |
| Durkin | Shut | Norseman Wiluna | 3.9 km North from Kambalda X: 372562 Y: 6551055 | 19.17 kt at 5.1% Ni | Mafic - thick tholeitic basalt, the Lunnon basalt | No elevated arsenic concentrations observed - all results observed at or below background levels | No hydrothermal halo observed surrounding the massive sulphides | Marston (1984) |
| Otter-Juan | Care and maintenance | Norseman Wiluna | 4.3 km NNW from Kambalda X: 371512 Y: 6551152 | 0.14 kt at 6.9% Ni | | | | Marston (1984) |

Barnes and Liu, 2012). The second important observation at Perseverance is the low arsenic content of samples collected along inferred fluid pathways such as faults and veins (mean concentrations ranging from below detection limit, 3 ppm to 90 ppm). However, anomalous As concentrations, mainly in the form of disseminated gersdorffite within the massive and matrix sulphides, have been observed in the Felsic Nose and the 1 A ore shoots (Diragitch, 2014), and arsenic is also present along the 1 A shear zone (3D model from BHP Billiton, (Barnes et al., 2011)) but in relatively low concentrations, and does not extend farther than the extent of mechanical remobilisation of the massive sulphides (200–300 m). At Perseverance, the restriction of As-enriched zones to mineralised (sheared or not) areas of the system, along with the low arsenic concentrations observed within the rest of the system, argues for a magmatic origin of the arsenides producing the elevated As concentrations.

The arsenic is interpreted as being incorporated in the sulphide liquid during thermo-mechanical erosion of the As-bearing graphitic sulphide sediment substrate by the komatiitic melt upon its emplacement, as inferred for other komatiite-hosted deposits such as Dundonald (Hanley, 2007) and Rosie (Godel et al., 2012). If this is the case, and the nickel arsenides are of magmatic origin, the present distribution of arsenic, concentrated in the re-mobilised, deformed and altered parts of the ore body (Diragitch, 2014), may simply reflect mechanical re-mobilisation and shearing of its As-enriched parts. We conclude that arsenic metasomatism does not extend along the 1 A shear zone farther than areas of physical re-mobilisation of the sulphides (Le Vaillant, 2014). The hydrothermal fluids that circulated through the system might therefore not have been carrying arsenic themselves, explaining the absence of a Ni-PGE hydrothermal enrichment around the massive sulphide mineralisation and along the main fluid pathways cross cutting the ore.

The study of hydrothermal haloes around these selected deposits provides key insights into the environment and the conditions necessary to create Ni-As-Co-Pd geochemical haloes around magmatic Ni-Cu-(PGE) deposits. Arsenic evidently plays a crucial role. An important conclusion is that the absence of As-related Ni-PGE hydrothermal haloes should not be regarded as a negative indicator in Ni-Cu-(PGE) sulphides exploration. Ni-As-PGE "stains" are unlikely to generate false positive anomalies, as the potential for Ni-Cu-(PGE) sulphides to not be present in the vicinity if Ni and PGE rich arsenides are detected, but false negatives are likely.

## 4. Weathering-resistant geochemical signals and indicator minerals

Potentially mineralised systems are only rarely found in fresh rocks at the surface, particularly in regolith-dominated terrains such as Australia. It is desirable to be able to recognise the geochemical signals of fertile mineral systems in weathered rocks in any terrain that has been subjected to deep weathering (e.g., Brazil, West Africa and regions in India). Typically, exploration programmes in such terrains involve air-core or percussion drilling through shallow transported cover to sample material from the "top of fresh rock", which in many cases comprises saprolite (in-situ weathered rock) (Anand and Paine, 2002). Barnes et al. (2014) compared fresh bedrock and "top of fresh rock" saprolite in the Agnew area in Western Australia and concluded that inter-element ratios of the rare-earth-elements, Zr, Ti, Cr and Ni in saprolite were preserved from the original unweathered fresh rock. Therefore bedrock lithologies were able to be mapped using saprolite geochemistry. The retention of Ni/Cr and Ni/Ti in weathered komatiites and basalts from the Agnew area is illustrated in Fig. 3b. Saprolite bottom-hole samples and fresh bedrock samples (from diamond drill core at depths greater than 50 m) are plotted from a study area approximately 5 km square centred around the Vivien gold mine north of Agnew, within a residual lateritic terrain. The Ni/Cr and Ni/Ti ratio-ratio plot is superimposed on the field defined by Barnes et al. (2004b) for channelised sheet flow facies (Kambalda-style) komatiites. Komatiites from the Agnew Komatiite formation and tholeiitic basalts from the Redeemer Formation (Hayman et al., 2015) define two distinct fields that overlap closely for weathered and fresh samples. A major advantage of this particular suite of elements (Ni, Cr and Ti) is their suitability for analysis using portable XRF devices at typical abundance levels (Le Vaillant et al., 2014). The same combination – reliable preservation through weathering, and amenability of pXRF analysis – applies to the ratio Zr/Ti that can be used as a proxy for contamination by enriched felsic material.

Mineral chemistry in lateritic terrains also has potential for exploration targeting of Ni-Cu-(PGE) sulphides. It was previously stated that Ru concentrations in chromite formed in komatiites could be used as a prospectivity indicator (Fiorentini et al., 2008; Locmelis et al., 2013). The application to weathered rocks of element ratios involving Cr in komatiites, (Locmelis et al., 2013) depends on the lack of independent mobility of Cr in solution during weathering. The interpretation of indicator trace element characteristics such as Ru depletion in detrital chromite grains depends very strongly on this assumption. The PGE behaviour and the nature of platinum group mineral inclusions in weathered chromites has not been systematically investigated, but there is evidence that cores of large chromite crystals, particularly Cr-rich ones (Garnier et al., 2008), preserve their primary chemistry through moderate degrees of weathering (Friedrich et al., 1981; Friedrich, 1984) even in lateritic environments (Summons et al., 1981; Michailidis, 1990) and possibly within diamictite glacial sediments (Salama et al., 2016). As chromite is a widespread component of resistant heavy mineral suites, studying their composition using LA-ICP-MS has real potential applications for exploration targeting of komatiite-hosted Ni-Cu-(PGE) deposits.

## 5. Conclusions

The effectiveness of different lithogeochemical techniques depends on scale, geological history and density of available data. All the various exploration techniques described above are summarised in Table 1, linked to the scale at which they are the most useful. For example, indicators of favourable volcanic setting, crustal contamination processes and magmatic sulphide formation are more likely to be seen at prospect scale, but in some cases can generate regional targets. In particular, useful information can be generated using ratios of the elements Ni, Ti, Cr and Zr. These elements can be measured in the field using pXRF instruments, and their ratios are reasonably robust under alteration and mild weathering. At deposit scale, the largest haloes, up to km scale, are generated by hydrothermal dispersion, but these are only formed in the presence of overprinting arsenic-bearing fluids and hence can easily give rise to false negatives. Chalcophile element anomalies, particularly PGE enrichment using proxies such as Pt/Ti, and Ni depletion in olivine or in olivine-rich cumulates, generate reliable vectors on a scale up to a few hundred metres, but are of limited value where orebodies are tectonically dismembered from their original host rocks.

All of the techniques outlined here are more effective when used in combination with one another. Effective exploration at all scales relies on integration of appropriate lithogeochemical signals with geophysical data, regional and local geological understanding, along with a large element of good luck. There are no geochemical magic bullets, but lithogeochemical data can be of great value in prioritising targets at all scales.

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