CHAPTER

2

REVIEW OF PREDICTIVE AND DETECTIVE EXPLORATION TOOLS FOR MAGMATIC NI-CU-(PGE) DEPOSITS, WITH A FOCUS ON KOMATIITE-RELATED SYSTEMS IN WESTERN AUSTRALIA

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CHAPTER OUTLINE

2.1 INTRODUCTION

About 60% of the world's nickel is currently produced from the exploitation and recovery of Ni-Cu-(PGE)-bearing sulfides associated with magmatic systems, mainly mafic and ultramafic magmatic intrusions and lava flows (Naldrett, 2004; Mudd, 2010). The remaining nickel production is almost entirely from limonitic and saprolitic laterite deposits (Golightly, 1981; Barnes and Lightfoot, 2005). The existing exploration problem for magmatic systems lies in the fact that they are extremely difficult targets. Indeed, the highly dynamic conduits where mineralization is

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commonly found, which are part of lithospheric plumbing systems and/or extensive volcanic fields where magma is transported, do not generally form large detectable footprints that can be easily followed up during exploration.

The purpose of this study is to review the application of exploration methods to search for magmatic systems, with a focus on komatiite-hosted systems where the most recent work has been carried out with a spatially constrained approach. The footprints, which are not necessarily geochemical in nature, are generally cryptic to most datasets, but can be revealed if the integration of various techniques is carried out at the appropriate scale. In this chapter, we will provide a general overview on the genetic process for orthomagmatic Ni-Cu-(PGE) systems with a mineral system approach (McCuaig et al., 2010). We will then describe the geochemical and geophysical techniques that are currently utilized, addressing how these exploration tools relate to each other and could be integrated at various scales.

2.2 NI-CU-(PGE) ORE-FORMING PROCESSES AND ASSOCIATED EXPLORATION TOOLS

2.2.1 ORE FORMING PROCESSES

A widely accepted working model for the genesis of magmatic Ni-Cu-(PGE) mineral systems involves the presence of a fertile magma (1), which reaches sulfide saturation (2) at various stages during emplacement and crystallization at different crustal levels; the sulfide liquid is then chemically enriched in metals and physically transported and accumulated in specific environments depending on a range of physical conditions (3). Barnes et al. (2016) comprehensively discussed the mineral system framework for magmatic mineral systems (Fig. 2.1).

The magma is the primary source of metals. Its fertility largely depends on the nature and degree of partial melting of the mantle source that generated it. Significant Ni-Cu-(PGE) deposits are known to be associated with a wide range of magma types, ranging from komatiites, ferropicrites, picrites, all the way to tholeiitic and alkali basalts. The varying nature of the magmas is not a controlling factor on the prospectivity of the given magmatic province but rather affects the metal content of the resulting sulfide mineralization.

In order to form nickel-rich sulfides, it is vital for the magmatic system to reach sulfide saturation prior to extensive olivine crystallization. Therefore, thermo-mechanical assimilation of sulfur-bearing lithologies during magmatic emplacement appears to be the most efficient way to form metal-rich sulfides. While this model is well established for komatiites, for which sulfide-rich exhalative and/or sedimentary rocks located proximal to the volcanic vent are the sulfur source (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), the question is still debated for the associated intrusive systems, for which isotope evidence is inconclusive as to the relative proportion in sulfur contribution between crustal and mantle reservoirs (e.g., Fiorentini et al., 2012b).

Once sulfide supersaturation is attained and a sulfide liquid is formed, chalcophile elements in the silicate melt partition into newly formed sulfide droplets. In order to be concentrated at an economic level, the sulfide droplets need to react with a sufficient amount of magma (Campbell and

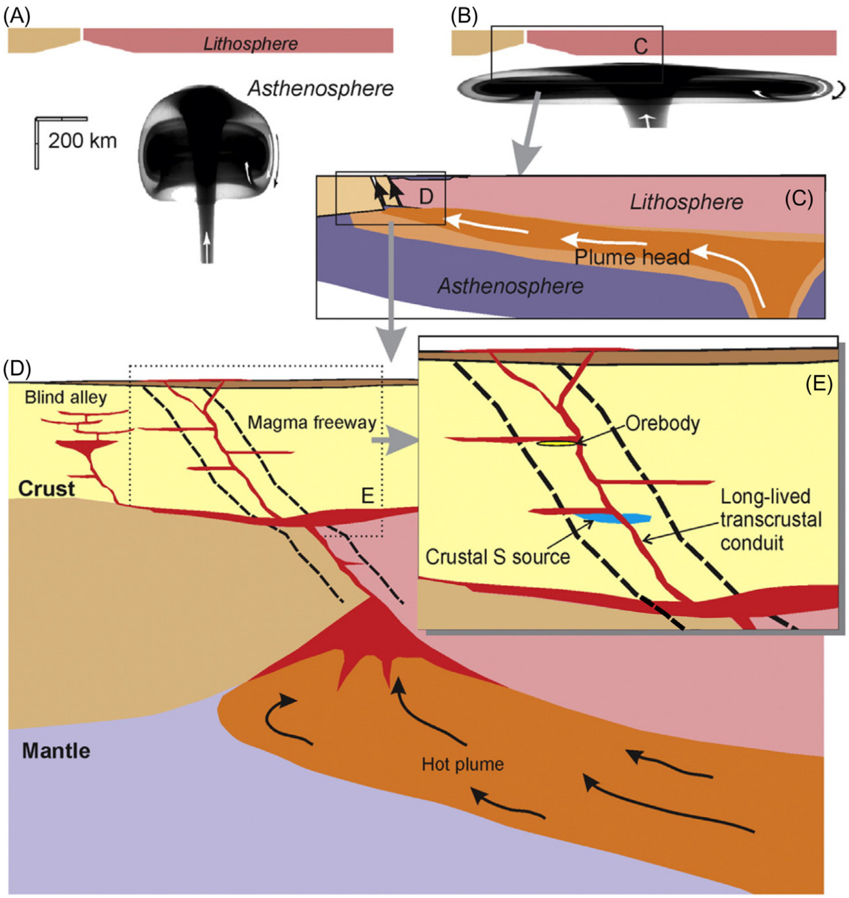

FIGURE 2.1

Schematic illustration of the lithospheric scale ore forming processes for the genesis of magmatic Ni-Cu-(PGE) deposits. (A) Starting plume ascending beneath an Archaean craton, within a few hundred kilometers of an original craton boundary. (B) Impingement and flattening of plume head beneath lithosphere. (C) Channeling of plume head and tail to thinnest lithosphere at craton margin, generation of continental rifting centered on original suture, and onset of high-Mg, low-T melts production. (D) Development of favorable and unfavorable environments for mineralization above the melting zone, showing the combination of long-lived mantle-tapping structure and high magma production giving rise to high flux “magma freeways” with potential for assimilation of crustal S, transport and deposition of magmatic sulfide ores.

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., 2016).

Finally, these sulfide droplets need to be concentrated in important quantities in a restricted locality to form ore bodies (Campbell and Naldrett, 1979; Naldrett, 1999). In komatiites, this concentration is generally thought to be achieved by gravitational settling of dense sulfide droplets to the bottom of lava flows (Naldrett, 1966; Ewers and Hudson, 1972), or freezing of dense sulfide liquid layers entrained at the base of the magmatic flow (Lesher and Campbell, 1993). In some intrusive systems, physical concentration may occur in response to changing geometry of the flow pathway and/or through dynamic interaction of the sulfide melt with surrounding country rocks, forming sulfide-rich breccias of variable nature (e.g., Robertson et al., 2015; Barnes et al., 2016; Locmelis et al., 2016).

Important primary magmatic processes leading to the genesis of Ni-Cu-(PGE) mineralization have been extensively studied and reviewed (e.g., Lesher and Keays, 1984, 2002; Lesher, 1989; Naldrett, 2004; Barnes, 2006b; Lesher and Barnes, 2009; Barnes et al., 2015). In order to translate the magmatic mineral system framework into an effective series of exploration targeting criteria, it is important to develop proxies that can image these genetic factors at the appropriate scale (McCuaig et al., 2010). Scale is fundamentally important in the development of an effective exploration protocol: while predictive tools can be applied at the regional to camp scale, detection techniques can be successfully applied from the camp to deposit and ore shoot scale (McCuaig et al., 2010; McCuaig and Hronsky, 2014).

2.2.2 CURRENT EXPLORATION METHODS

Predictive techniques are the main targeting methodology when exploring at the craton- to terrane-scale, based on favorable tectonic setting and volcanic environment (McCuaig et al., 2010; McCuaig and Hronsky, 2014). Detection techniques, both geophysical and geochemical in nature, are increasingly more effective as exploration evolves from regional scale all the way to camp, prospect, deposit, and ore shoot scales. However, both the predictive and detective techniques that have been developed to explore for magmatic mineral systems over the last four decades have only had limited success. A summary of all these techniques is presented in Table 2.1.

2.2.3 PREDICTIVE TECHNIQUES AT REGIONAL SCALE

When exploring at the regional scale, explorers look for (1) favorable tectonic environments along with (2) the most prospective geological setting. For magmatic Ni-Cu-(PGE) systems, favorable tectonic environments are represented by large crustal scale structures favoring 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, 2014) and continental rift zones subsequently inverted by polyphase deformation (Beresford et al., 2007; McCuaig et al., 2010; Fiorentini et al., 2012b), as shown in Fig. 2.2. 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 of any given lithospheric block, whereas the location of the highly prospective paleo-margins of the terranes that assembled to form the craton would be blind to such techniques. In order to image the paleo-margins and reveal the presence of intra-cratonic prospective areas, it is possible to make use of spatially constrained isotopic terrane mapping. In fact, maps of whole-rock Sm-Nd (εNd) model ages of granitoids indicate the presence of ancient craton boundaries (Fig. 2.2). The addition of

Table 2.1 Summary of the Various Exploration Tools Described in this Paper

Regional Scale		Camp to Prospect Scale		Deposit Scale	
Favorable Tectonic Settings:		*Channelized Volcanic Environments:*		*Evidences of Sulfide 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 chalccophile elements (Ni, Cu, Co and PGE) Whole rock and Ni in olivine	*Barnes et al., 1988a; Barnes and Picard, 1993; Lesher et al., 2001*
Inverted continental rift zones	*Beresford et al., 2007; McCuaig et al., 2010; Fiorentini et al., 2012b*	Exploration tool for komatilte-hosted systems: Potentially using pXRF data	Ni/Ti vs Ni/Cr diagrams, *(Le Vaillant et al. 2014)*	Ruthenium depletion in chromite grains (komatilte hosted systems) – possible applications in lateritic terranes	*Fiorentini et al. 2008; Locmelis et al., 2011, 2013;*
		Evidence of Crustal Contamination:			
		Sulfur isotope analyses to test crustal assimilation models	*Fiorentini et al., 2012a*		
Exploration tools:	Magnetotellurics, Aeromagnetics, Seismics, Gravity, Sm-Nd model Age maps, Lu-Hf isotopes on zircons *(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, 2015b)*	Anomalous enrichment in incompatible elements such as Zr, Th, LREE	*Lesher et al., 2001; Barnes and Hill, 2004b; Fiorentini et al., 2012b*	Exploration tool:	Whole rock analyses, Laser ablation ICP-MS Analyses of olivine and chromite to evaluate their Ni or Ru content
		Possible pervasive contamination signals in certain cases (e.g., Black Swan, Perseverance)	*Barnes et al., 1988c, 2004a, 2007; Barnes and Fiorentini, 2012;*	*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 sulfides (Barnes et al., 2013; Heggie et al., 2012).*	
Areas of Enhanced Magmatic Flux:		Exploration tools:	Laboratory geochemical analyses, portable XRF (pXRF) analyses potentially directly on the field *(Le Vaillant et al., 2014)*	*Empirical Detection Tools:*	
High proportions of high MgO komatiite magmas, and abundance of strongly adcumulate olivine-rich cumulates	*Barnes and Fiorentini, 2012*			Use of Ni/ Cr to delineate ore-related channels in komatiite hosted systems	*Barnes and Brand, 1999; Barnes et al., 2013*

(*Continued*)

Table 2.1 Summary of the Various Exploration Tools Described in this Paper ***Continued***

Regional Scale	Camp to Prospect Scale	Deposit Scale
Favorable Tectonic Settings:	***Channelized Volcanic Environments:***	***Evidences of Sulfide Accumulation and/or Extraction:***
	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)	*Example: delineation of ore shoots around the Kambalda Dome, Western Australia (Barnes and Brand, 1999)* Airborne and down hole electromagnetic surveys
Exploration tools: Regional airborne aeromagnetic Surveys *(Barnes et al., 2004a; Grguric and Riley, 2006; Fiorentini et al., 2007)*	*Evidences of Sulfide Accumulation and/or Extraction:*	*Example: The Nova discovery (Western Australia) was mode when testing a large and strong EM anomaly (ASX Announcement – 26.07.2012)*
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 Yilgam Craton, and convergence of multiple faults including the Mundrobilla fault) (Pers. Comm. John Hronsky)	Positive and negative anomalies in chalccophile elements (Ni, Cu, Co and PGE) Whole rock and Ni in olivine — *Barnes et al., 1988a; Barnes and Picard, 1993; Lesher et al., 2001*	*Hydrothermal Ni-As-PGE Haloes:*
	Exploration tool: Whole rock analyses, Laser ablation ICP-MS analyses of olivines to evaluate their nickel content	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-sulfides. Shown in Komatiite hosted system, applicable to any type of magmatic Ni-Cu-(PGE) deposit.
	Examples: LowNi contents of oivines 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)	*Le Vaillant, 2014; Le Vaillant et al. 2015a,b)* *Example: Hydrothermal geochemical halo observed surrounding the Miitel and the Sarah's Find deposits, Western Australia (Le Vaillant et al. 2015a,b)*

Modified from Le Vaillant, M., Fiorentini, M.L., Barnes, S.J., 2016b. Review of lithogeochemical exploration tools for komatiite-hosted Ni-Cu-(PGE) deposits. J. Geochem. Explor. 168, 1–19.

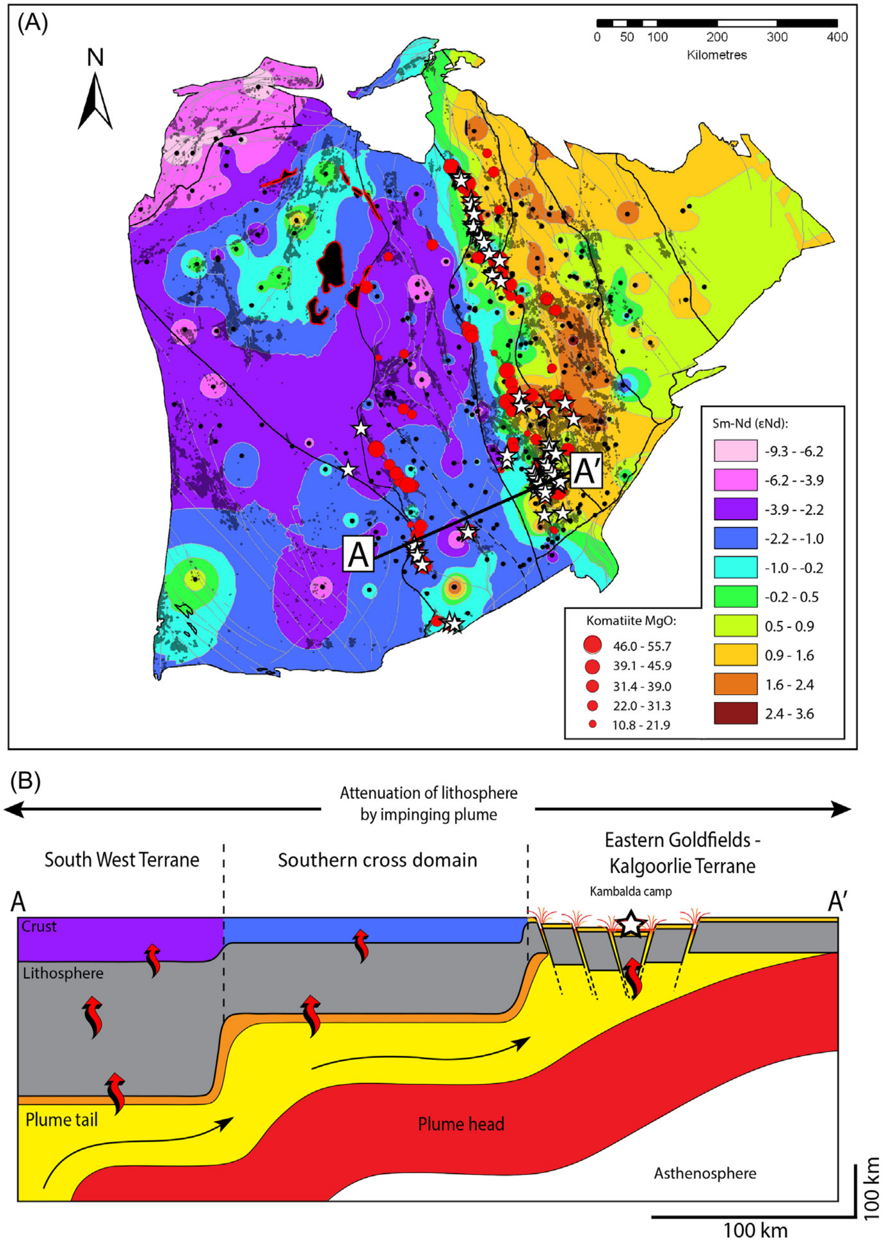

FIGURE 2.2

(A) Sm-Nd (εNd) isotopic map (geometric interval) highlighting the internal architecture of the Yilgarn craton, Western Australia, and showing the location of komatiite-hosted nickel deposits along its paleo-margins (white stars). (B) Interpreted lithospheric cross-section based on the Sm-Nd isotopic mapping.

Adapted from Mole, D.R., Fiorentini, M.L., Cassidy, K.F., Kirkland, C.L., Thebaud, N., McCuaig, T.C., et al., 2013. Crustal Evolution, Intra-Cratonic Architecture and the Metallogeny of an Archaean Craton. Geological Society, London, Special Publications 393.

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, 2014).

Currently, aeromagnetic and geological maps are still the main tools in practice to identify favorable tectonic settings and host lithologies, at a range of scales. For example, to assist in exploration targeting for komatiite systems, Perring et al. (2015a, 2015b) have proposed the existence of accretionary growth faults, recognizable in regional magnetic and gravity patterns, as primary controls on the location of mineralized dunite channels in the Agnew-Wiluna greenstone belt of Western Australia. However, in poorly exposed terranes 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).

When exploring for magmatic Ni-Cu-(PGE) deposits, explorers look for areas of enhanced magmatic flux, which are reflected for example in the presence of large sulfide globules, in excess of 1 cm, indicating that the transporting magma was capable of generating a massive sulfide accumulation (Barnes et al., 2017). In the case of komatiites, proxies for enhanced flux are also high MgO concentrations and abundance of strongly olivine mesocumulate-adcumulate textured rocks (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 favorable lithologies. This was one of the main exploration tools during the nickel boom in 1966−71 in Western Australia (Woodall and Travis, 1969; Ross and Travis, 1981; Marston, 1984; Hronsky and Schodde, 2006). Where high MgO rocks are serpentinized, they generate strong bulls-eye magnetic anomalies, such as at the 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 favorable tectonic environment such as a trans-lithospheric fault with areas of high magmatic flux within a large igneous province is a highly favorable indicator of nickel endowed mining camps, such as the Kambalda camp where the first nickel discoveries were made in the mid 1960s (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 recent world-class discoveries at Nova Bollinger and Nebo Babel in the Fraser belt and West Mustgrave areas of Western Australia, respectively, are good examples of mineralized systems that were discovered using predictive targeting at the craton scale, looking for areas with evidence of major focused mantle-derived magmatism with anomalous lithospheric architecture.

2.2.4 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 magmatic units that may have reached sulfide saturation due to crustal assimilation. As an example, Zr and Ti are relatively immobile and incompatible in crystallizing 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 crystallization (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). This methodology has been successfully applied in komatiite exploration, where pervasive crustal contamination signals are observed over several km of strike, such at the Black Swan komatiite complex (Barnes et al., 2004a) as well as at the Perseverance and Mount Keith ultramafic complexes (Barnes et al., 1988b), both in the Yilgarn craton of Western Australia, where komatiites were erupted onto and within sulfide-bearing felsic country rocks (e.g., Fiorentini et al., 2007).

Barnes and Fiorentini (2012) showed that, at the scale of greenstone belts and terranes, prospective belts tend to contain significantly higher proportions of contaminated komatiites. The mineralized 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 sulfidic sediments, as at Kambalda, signals of contamination can be weak and spatially limited even in well-mineralized flows (Lesher and Arndt, 1995; LaFlamme et al., 2016), where the contamination seems to be limited to the flanking sheet flow facies, and absent within the most active, central part of the the channel where the ore-forming magma has been flushed out by ongoing flow (Lesher et al., 2001; Barnes et al., 2013b).

However, the application of this geochemical approach may lead to the identification of a high rate of false positive targets. First of all, the nature of the geochemical nature is very dependent upon the type of contaminant, some of which may not leave behind an easily detectable footprint. Furthermore, it is clear that not all magmatic conduits that were emplaced dynamically along any plumbing system are mineralized (e.g., Paringa Balsalts, Kambalda; Redman and Keays, 1985). However, combining evidence of crustal contamination with other observations can help identify these false positives.

2. When exploring for komatiite-hosted deposits, channelized volcanic environments are the most prospective settings (Barnes and Brand, 1999; Lesher et al., 2001; Barnes et al., 2004b; Fiorentini et al., 2012b). These can be detected with a series of geochemical criteria (Fig. 2.3), which are particularly useful where original rock textures are unrecognizable. For example, a Ni/Ti vs Ni/Cr diagram can be used to delineate favorable volcanic environments; Ni/Ti will correlate with original olivine content constraining the silicate nickel background and highlighting subtle sulfide-related nickel enrichment. This can be combined with the Ni/Cr ratio, which gives information on the volcanic environment.

Empirical observations show that in komatiite systems prospective olivine-rich channel facies rocks tend to have higher Ni/Cr ratios than unprospective non-channel facies rocks of

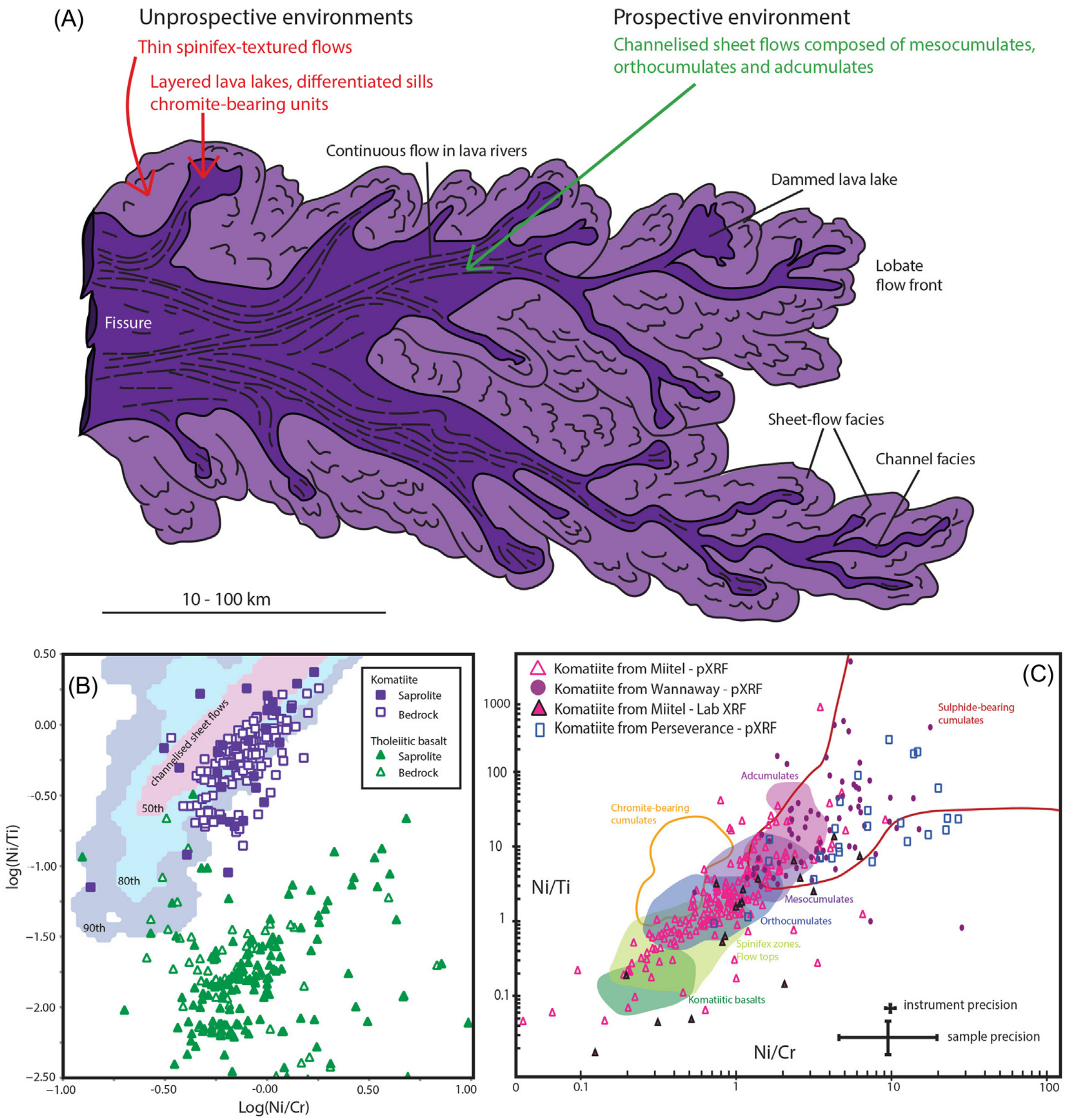

FIGURE 2.3

(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, M., Barnes, S.J., Fisher, L., Fiorentini, M.L., Caruso, S., 2014. Use and calibration of portable X-Ray fluorescence analysers: application to lithogeochemical exploration for komatiite-hosted nickel sulphide deposits. Geochem. Explor. Environ. Anal. 14, 199–209.

otherwise similar composition (Barnes, 1998), such as for example the mineralized Kambalda-style ore environments. These are characterized by high Ni and low Cr contents of sulfide-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 et al., 1981). 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 favorable sulfide 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, Cape Smith belt, Northern Quebec (Barnes and Picard, 1993; Lesher et al., 2001), 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 (Le Vaillant et al., 2014), as shown in Fig. 2.3C.

3. Chalcophile element anomalies associated with magmatic sulfide 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 komatiite-hosted Perseverance deposit, Agnew Wiluna greenstone belt, Western Australia, the observed extensive depletion of nickel in olivine is indicative of sulfide 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. However, some mineralized komatiite 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 using these geochemical tools.

The komatiite-hosted Perseverance deposit represents an extremely dynamic magmatic system with a lasting magma flow or multiple flows without solidification in between, resulting in pervasive felsic footwall assimilation. Extensive olivine-sulfide equilibration in such a dynamic system gave rise to Ni depletion in olivine in a very large volume of preserved cumulates. On the other hand, although the Kambalda magmatic system as a whole contains comparable volumes of sulfide ore as Perseverance, mineralization at Kambalda occurred within relatively low volume, strongly channelized magma flows with a highly localized external S source. In the Kambalda deposit, Ni depletion in olivine is restricted to the immediate surrounding rocks. Furthermore, the extent of Ni depletion depends strongly on the R factor, i.e. the mass ratio of silicate magma to sulfide liquid that equilibrate. Where R factors are relatively low, as at Perseverance, ore tenors are lower, and Ni depletion in silicate magma and olivine correspondingly is greater, relative to high R factor deposits with high Ni tenors and only minor Ni depletion in olivine (Barnes et al., 2013a).

4. At the camp to prospect scale, multiple sulfur isotopes represent a very informative tool both for prediction and detection of magmatic mineral systems. From a predictive perspective, multiple sulfur isotopes support the working hypothesis that crustal assimilation is key to sulfide saturation at least in komatiite systems (Lesher and Groves, 1986a), where the source can vary from exhalative dominated reservoirs—mostly associated with felsic volcanism in

VMS type settings (Fiorentini et al., 2012a)—all the way to sulfidic sediments in abyssal oceanic planes (La Flamme et al., 2016). In mafic hosted systems, sulfur isotopes have been used to either advocate for a mantle source of sulfur or/and to show the extreme complexity of the ore forming process, with assimilation of different crustal sulfur reservoirs at variable depths over the emplacement and crystallization history of any given magmatic system (Seat et al., 2009; Ripley, 2013).

2.2.5 DETECTIVE TECHNIQUES AT DEPOSIT SCALE

As the scale of exploration closes in to the camp and deposit scales, the availability of detective techniques increases (McCuaig et al., 2010). Over the years, several detection techniques have been developed for magmatic Ni-Cu-(PGE) systems. However, their efficiency is still limited, mainly due to the small size and ribbon-like geometry of most Ni-Cu-(PGE) sulfide ore bodies, especially the ones associated with komatiite magmas (Fig. 2.3). The main available exploration tools for magmatic sulfide systems 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) as an indication of sulfide segregation and accumulation (e.g., Lesher et al., 2001; Barnes et al., 2004b; Arndt, 2005). Fiorentini et al. (2010, 2011) suggested that enrichment and depletion should not be considered in absolute terms, as they may vary according to different magmatic provinces and magma types. They investigated the PGE background concentrations of basalts, ferropicrites and komatiites, in order to define the various controls for PGE variation, and subsequently isolate PGE variability related to sulfide saturation. Platinum-group variability has been utilized to refine ore genetic concepts (e.g., Norilsk-Talnakh deposit; Arndt, 2005) or predict the mineralization potential of different magmatic provinces (e.g., Deccan Traps; Krishnamurthy, 2015). However, the most detailed spatially constrained studies were carried out for komatiite systems. At the Long Victor (Kambalda) and Maggie Hays komatiite-hosted nickel-sulfide deposits, Western Australia, Barnes et al. (2013b) and Heggie et al. (2012) observed localized subtle PGE enrichments and/or depletions extending up to 400 m away from mineralization, thus considerably enlarging the footprint of those notably small targets. Similarly to PGEs, 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 magmatic systems, especially Archean komatiites, which are almost universally pervasively altered, and to (2) the lower sensitivity of Ni relative to PGEs to sulfide-related depletion due to its much lower partition coefficient (Duke and Naldrett, 1978; Duke, 1979). On the other hand, while minero-chemical analyses for Ni in olivine are very affordable, PGE-based techniques generally require expensive high-precision analyses.
2. A similar limitation applies to the use of Ni/Cr ratios, which can delineate ore-related channels within broad komatiitic volcanic fields (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 komatiite lava channels tend to have higher Ni/Cr even in samples that are not mineralized. There are two reasons for this: the magmas tend to be hotter, and therefore less likely to be chromite-saturated; and even when the magmas were

chromite-saturated (e.g., Mt Keith; Barnes et al., 2011), chromite crystallization seems to be suppressed in high-flux channel settings, especially where sulfide is present (Woolrich et al., 1981; Barnes, 1998). 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 olivine cumulate-rich komatiites (Fig. 2.4). Both in extrusive (e.g., Long-Victor deposit at Kambalda) and intrusive systems (e.g., Maggie Hays, Lake Johnson greenstone belt), variations in Pt/Ti and Pd/Ti can be detected in essentially sulfide-free rocks some 400 m away from orebody. In the Kambalda case, this takes the form both of PGE depletion in flanking flow tops and PGE enrichment closer to orebody within the channel. Both the depleted and enriched signals extend up to 450 m away from the 0.4 wt% Ni grade shell (the effective limit of detectable disseminated sulfides) and are much clearer than the very subtle variation in Ni/Cr between channel and flank facies (Fig. 2.4A,B). Using the Ni/Cr ratios does not appear to have 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 sulfide shell, but the Pt/Ti and Pd/Ti define particularly clear vectors of systematic increase towards orebody. Values above 1 (mantle normalized value) appear up to 650 m away with a systematically increasing trend developed within the inner 250 m (Fig. 2.4).

3. The detection of ruthenium depletion in chromite grains, obtained by laser-ablation ICP-MS analysis of chromite grains either in situ or from mineral separates, shown as characteristic of mineralized komatiites by Locmelis et al. (2013), can potentially be used to discriminate between mineralized and barren komatiite flows (Fiorentini et al., 2008; Locmelis et al., 2011; Locmelis et al., 2013). Care must be taken to compare rocks that cooled at similar rates, as cooling rate seems to have an effect on Iridium-group PGE (IPGE) concentrations in chromites (Pagé and Barnes, 2016).
4. Finally, the evaluation of the thickness of sedimentary rock units at basal komatiite contacts could potentially be used for exploration, as a tight mutually exclusive relationship between the distribution of sulfidic sedimentary rocks and Ni-Cu-(PGE) sulfide orebody 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 50−100 m away from massive sulfides, mainly because of the dynamic nature of the ore-forming channels and removal of early ore-forming magma by the later magma pulses. Moreover, these techniques rely on the present geometry being similar to the one upon emplacement, whereas komatiite-hosted Ni-Cu-(PGE) systems have commonly undergone polyphase deformation (e.g., Duuring et al., 2007; Layton-Matthews et al., 2007; Duuring et al., 2010; Duuring et al., 2012), rendering these detection tools largely 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

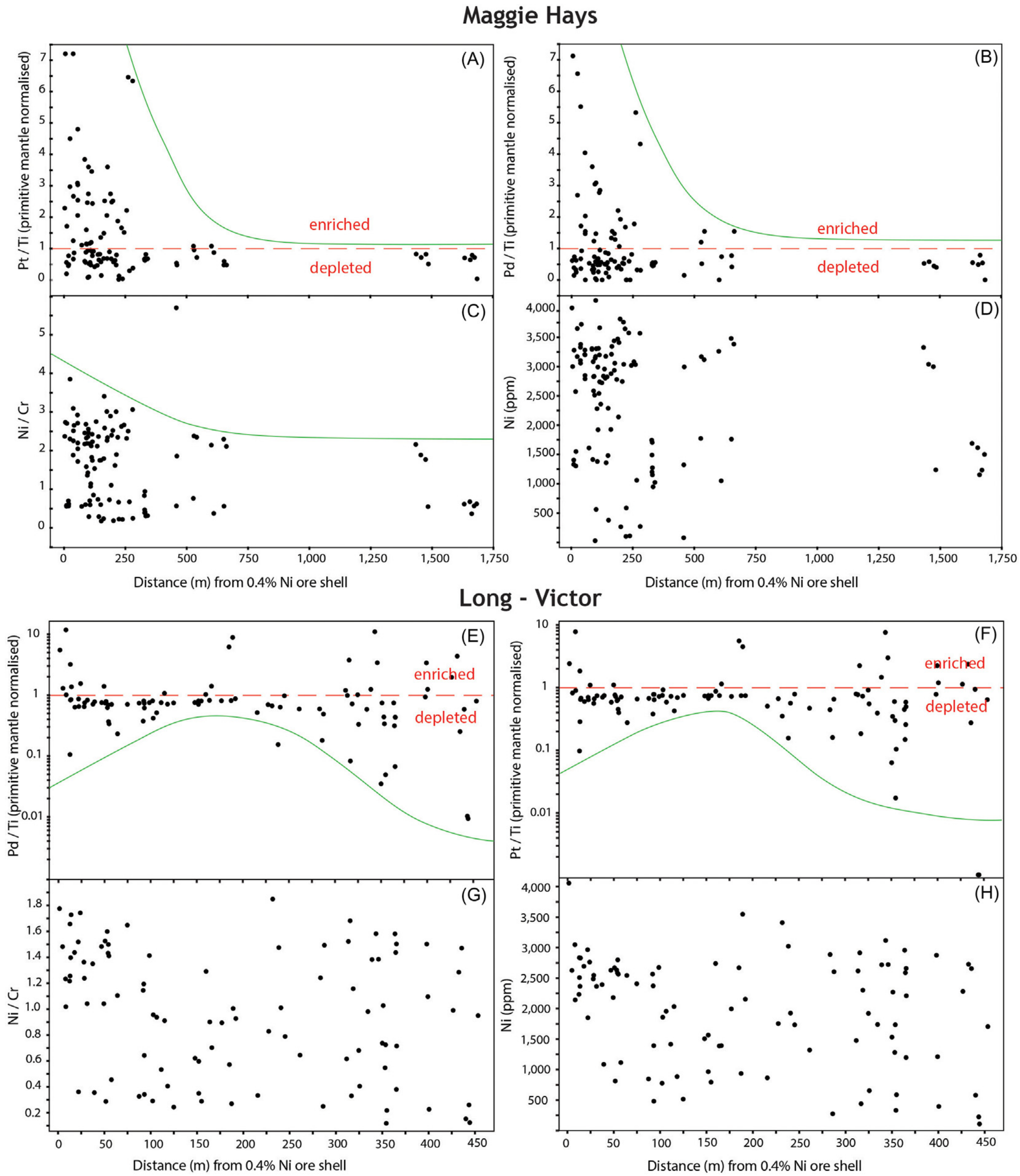

FIGURE 2.4

Comparison between the spatial extent of anomalous Ni/Cr and PGE haloes at Maggie Hays and Long Victor.

Modified from Barnes, S.J., Heggie, G.J., Fiorentini, M.L., 2013b. Spatial variation in platinum group element concentrations in ore-bearing komatiite at the Long-Victor deposit, Kambalda Dome, Western Australia: enlarging the footprint of nickel sulphide orebodies. Econ. Geol. 108, 913–933.

are generally very efficient to detect massive nickel-sulfide 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 size of the target, and varies between 0.5−1.5 times the smaller dimensions of the ore body, therefore generally extending 50−150 m from massive sulfides (Peters, 2006), making it a highly effective tool to follow brownfield ore body extensions. However, in Australia particularly, large amounts of saline groundwater and salt are present in the cover, challenging EM interpretations (González-Álvarez et al., 2016). And for komatiite-hosted Ni-Cu-(PGE) deposits, the following characteristics give rise to several limitations for geophysical methods: ore bodies are commonly small and deep seated, barren sedimentary and exhalative sulfide units are commonly in close spatial association with the ore bodies. Finally, the main drawback of DHEM is the high false positive rate due to EM anomalies associated with barren sulfidic or graphitic metasediments, which makes it difficult to discriminate nickel-rich from barren sulfide bodies (Peters, 2006).

All exploration tools described above are summarized in Table 2.1. In brief, magmatic Ni-Cu-PGE deposits remain very difficult exploration targets. Their general location can be reasonably well predicted owing to an extensive knowledge of their genetic processes, but to this date there are no effective predictive or detection techniques (geochemical or geophysical) that allow explorers to define and prioritize targets from sparse drilling. For example in Western Australia the rate of discovery of magmatic mineral systems has slowed down dramatically since the initial surge of exploration success for komatiite-hosted deposits between 1966 and 1973 (Hronsky and Schodde, 2006). Undiscovered deposits are highly likely to exist at depth, even in mature well-explored terranes, where they are likely to be 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.

2.3 HYDROTHERMAL REMOBILIZATION 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-sulfide bodies has the potential to create a relatively large dispersive footprint with specific mineralogical and lithogeochemical characteristics. 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 sulfide units adjacent to the nickel-sulfide deposits. At Thompson, this enrichment is interpreted as being either created during the mobilization 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 meters away from massive sulfides.

In addition, there are an increasing number of studies on hydrothermal nickel and/or PGE accumulations. In the Sudbury camp, the low-sulfide, Pt- and Pd-rich haloes (150 m away from massive sulfides) around vein-type Ni-Cu-(PGE) ores in the footwall of the Sudbury Igneous Complex (SIC), have been interpreted as the result of remobilization of PGE (mainly Pt and Pd) from differentiated sulfide liquids by late magmatic-deuteric and/or hydrothermal fluids by some researchers (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 remobilization of large amounts of nickel from sulfide sources, on a scale of hundreds of meters up to kilometers in some specific cases (González-Álvarez et al., 2010, 2013a, 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 behavior of Ni, Pd, and Pt in hydrothermal fluids (Barnes and Liu, 2012; Yuan et al., 2015; Le Vaillant et al., 2016a) 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 remobilize nickel and PGE from a massive sulfide source and potentially create hydrothermal haloes useful for exploration targeting.

Le Vaillant et al. (2016b) investigated the nature of hydrothermal geochemical haloes around komatiite-hosted Ni-Cu-PGE deposits 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. 2.5). The same methodology was applied at five komatiite hosted localities (Fig. 2.5). Results obtained for the various "hydrothermal halo" case studies are compared in Table 2.2. While the Miitel and the Sarah's find deposits display large Ni-As-PGE (Pd, Pt) hydrothermal haloes (Figs. 2.6 and 2.7), the Otter–Juan, Durkin and Perseverance ore bodies are devoid of any detectable halo, even though all these deposits have undergone similar phases of deformation and alteration. It is argued that these systems did not attain the necessary conditions allowing Ni and PGEs to be either incorporated in hydrothermal fluids and mobilized or even just re-deposited (Le Vaillant et al., 2016b).

The Miitel, Otter-Juan and Durkin ore shoots are directly comparable case studies as they are Kambalda-style type 1 deposits (Lesher, 1989; Hill and Gole, 1990) hosted at the basal contact between channelized komatiites and footwall basalts. In addition, all these komatiite localities have undergone similar metamorphic and alteration processes. However, while the Miitel deposit is extensively overprinted with arsenic metasomatism (values ranging from 35 to 2,405 ppm As), the Durkin and Otter-Juan deposits are devoid of it (maximum of 60 ppm As measured, with most values below detection limits). Le Vaillant et al. (2016b) put forward the hypothesis that the presence of arsenic plays a first order control in the development of a geochemical halo. According to

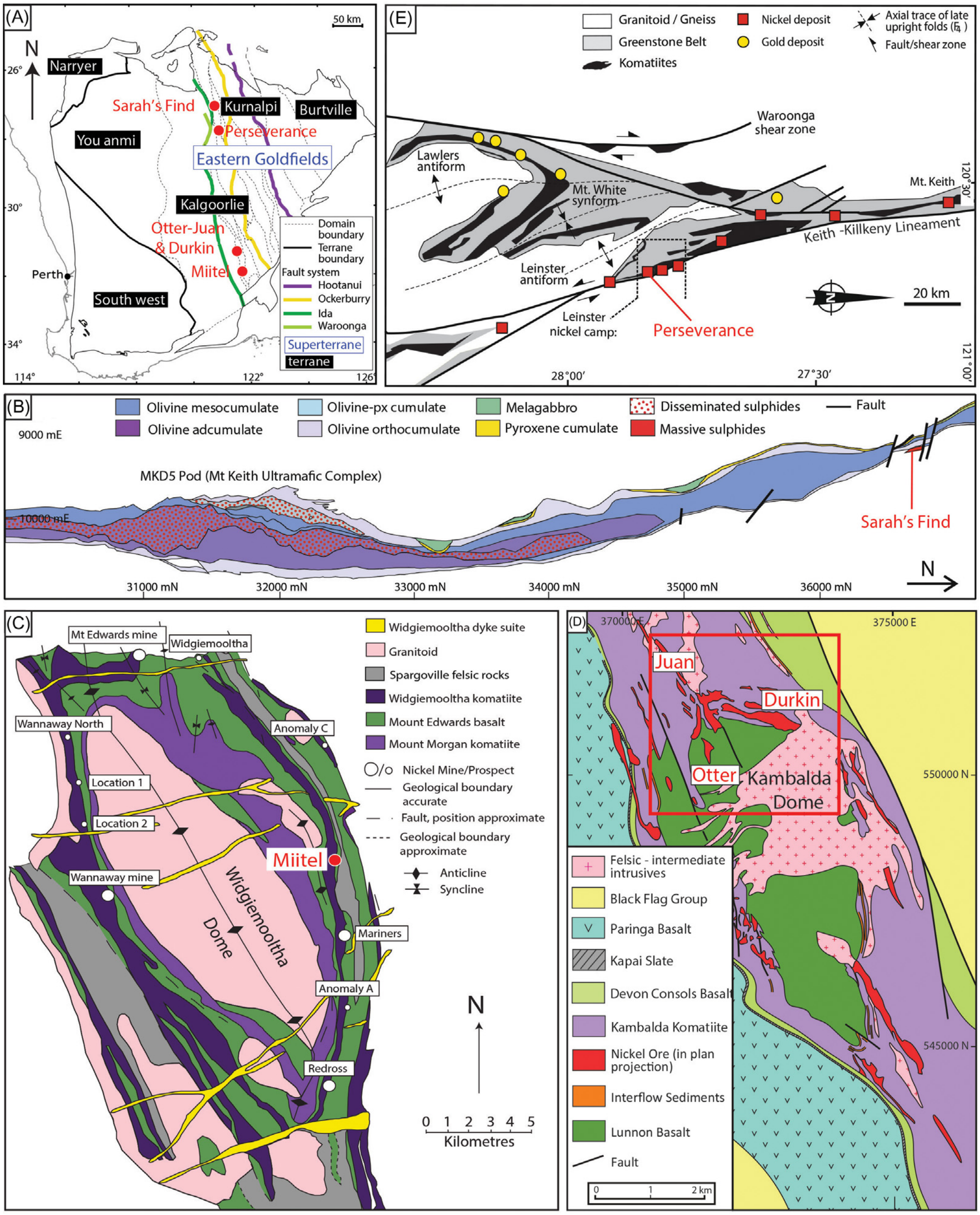

FIGURE 2.5

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 Fiorentini et al., 2007; Rosengren et al., 2007; Barnes et al., 2011). (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 Willet 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).

Table 2.2 General information and summary of the results obtained during the study of hydrothermal haloes around various Australian komatiite-hosted nickel sulfide 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 tholeiitic 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 sulfide mineralization	Cairns et al. (2003); Le Vaillant et al. (2015c), Le Vaillant (2014)
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 sulfides and areas where they have been mechanically remobilised — not widespread	No hydrothermal halo observed surrounding the massive sulfides (only mechanical remobilisation of the Sulfides)	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), Duuring et al. (2010), Barnes et al. (2011), Le Vaillant (2014)

Sarah's find	Prospect	Agnew Wiluna	Northern part of the Mont 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 sulfide mineralization (Le Vaillant et al. 2015b)	Burt and Sheppy (1975), Dowling and Hill (1990), Hill (1995), Rosengren et al. (2005, 2007), Fiorentini et al. (2007), Le Vaillant et al. (2015b)
Durkin	Shut	Norseman Wiluna	3.9 km North from KambaldaX:372562 Y:6551055	19.17 kt at 5.1 % Ni	Mafic –thick tholeiitic basalt, the Lunnon basalt	No elevated arsenic concentrations observed – all results observed at or below background levels	No hydrothermal halo observed surrounding the massive sulfides	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	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 sulfides	Marston (1984)

Modified from Le Vaillant, M., Fiorentini, M.L., Barnes, S.J., 2016b. Review of lithogeochemical exploration tools for komatiite-hosted Ni-Cu-(PGE) deposits. J. Geochem. Explor. 168, 1–19.

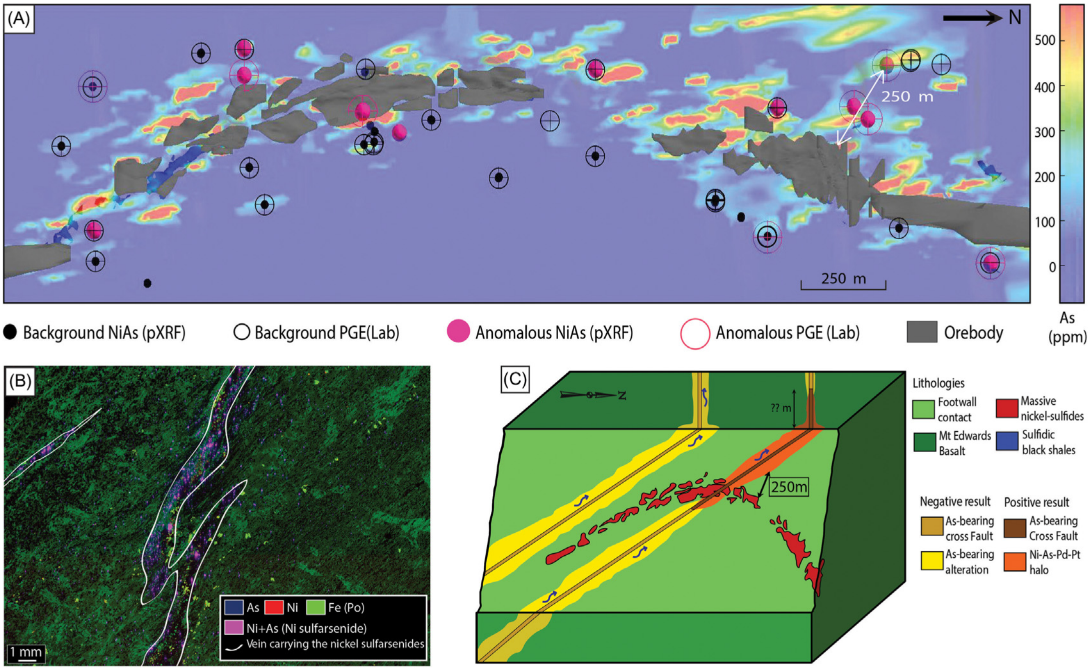

FIGURE 2.6

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 color 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 sulfides.

Modified from Le Vaillant, M., Barnes, S.J., Fiorentini, M.L., Miller, J., McCuaig, T.C., Muccilli, P., 2015a. A hydrothermal Ni-As-PGE geochemical halo around the miitel komatiite-hosted nickel sulphide deposit, Yilgarn Craton, Western Australia. Econ. Geol. 110, 505–530.

the model, arsenic-rich fluids, such as those commonly related to orogenic gold events (Eilu and Groves, 2001), remobilized Ni and PGEs from the massive sulfides (Wood, 2002), subsequently re-depositing them as nickel-arsenides within a geochemical halo surrounding the magmatic nickel-sulfide ore (Le Vaillant et al., 2015a).

Le Vaillant et al (2016b) investigated in detail the nature of metal remobilization and the formation of detectable hydrothermal haloes surrounding nickel-sulfide deposits, in an attempt to better document the size and geometry of these targets that effectively enlarge the footprint of primary magmatic mineralization. The study of hydrothermal haloes around selected deposits provided key insights into the environment and the conditions necessary to create Ni-As-Co-Pd geochemical

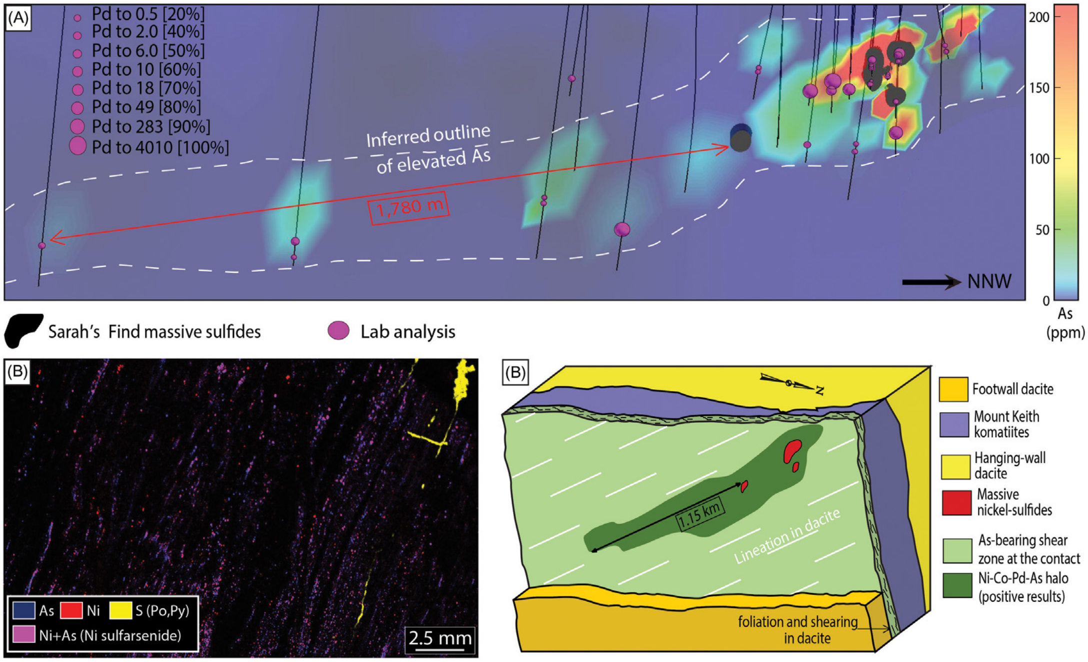

FIGURE 2.7

Summary of results from the study of the Sarah's Find deposit(A) 3D visualization of concentrations in Pd of all analyzed samples, combined with a color 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, M., Saleem, A., Barnes, S., Fiorentini, M., Miller, J., Beresford, S., et al., 2015b. Hydrothermal remobilisation around a deformed and remobilised komatiite-hosted Ni-Cu-(PGE) deposit, Sarah's Find, Agnew Wiluna greenstone belt, Yilgarn Craton, Western Australia. Mineral. Deposita, 1–20.

haloes around magmatic Ni-Cu-(PGE) deposits. The authors concluded that 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 exploration for Ni-Cu-(PGE) sulfides. They suggested that Ni-As-PGE "stains" are unlikely to generate false positive anomalies, but false negatives are likely (Le Vaillant et al., 2016b).

2.4 WEATHERING-RESISTANT GEOCHEMICAL SIGNALS AND INDICATOR MINERALS

Potentially mineralized systems are only rarely found in fresh rocks at the surface, particularly in regolith-dominated terrains of continental land masses that occur at tropical latitudes. It is desirable to be able to recognize the geochemical signals of fertile mineral systems in weathered rocks in any terrain that has been subjected to deep weathering (e.g., Australia, Brazil, West Africa, India). Typically, exploration programs 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.

Le Vaillant et al (2016b) plotted saprolite bottom-hole samples and fresh bedrock samples (from diamond drill core at depths greater than 50 m) from a study area approximately 5 km square centered around the Vivien gold mine north of Agnew, within a residual lateritic terrain (Fig. 2.3B). The Ni/Cr and Ni/Ti ratio-ratio plot is superimposed on the field defined by Barnes et al (2004b) for channelized 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) sulfides. 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 depend on the lack of independent mobility of Cr in solution during weathering (Locmelis et al., 2013). The interpretation of indicator trace element characteristics such as Ru depletion in detrital chromite grains depends very strongly on this assumption. The PGE behavior 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.

2.5 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 summarized in Table 2.1, linked to the scale at which they are most useful (Fig. 2.8). For example, indicators of favorable volcanic setting, crustal contamination processes, and magmatic sulfide formation are more likely to be used 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

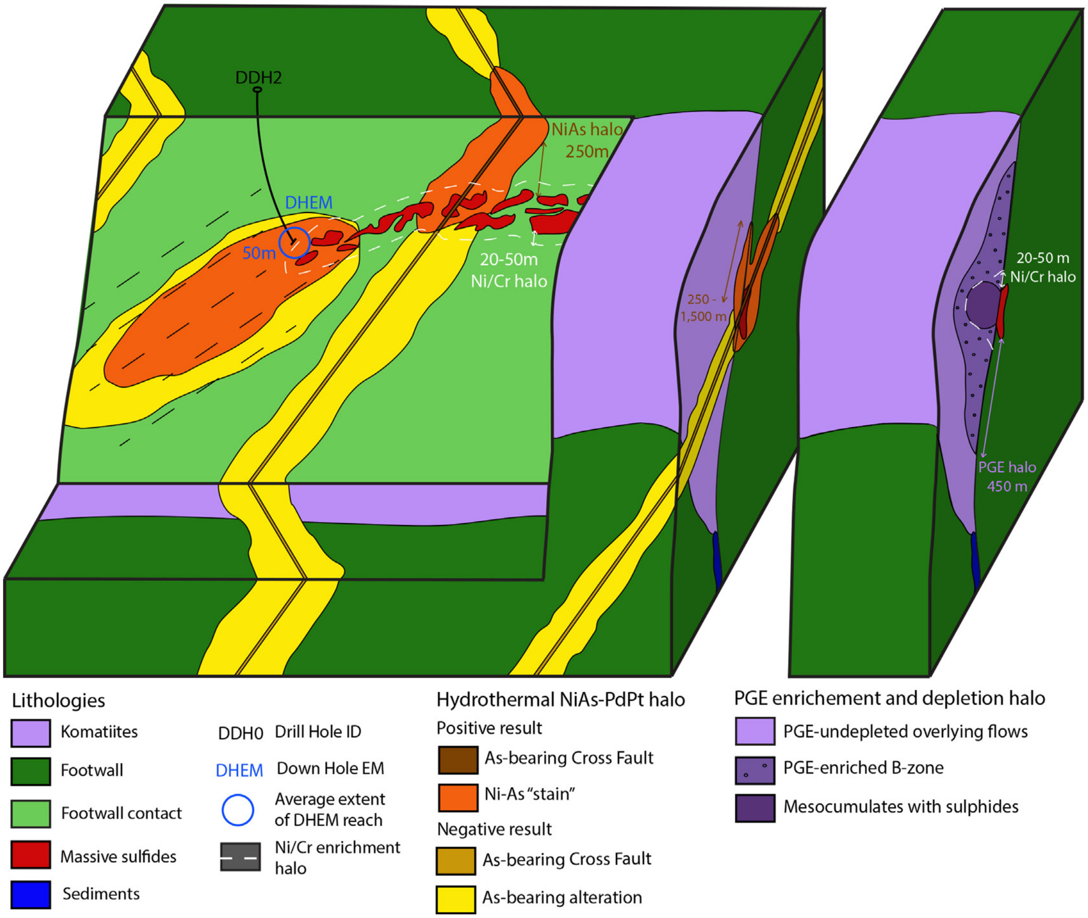

FIGURE 2.8

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

elements can be measured in the field using pXRF instruments, as 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 meters, 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 prioritizing targets at all scales.

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