

Review

Value of mineral deposits associated with mafic and ultramafic magmatism: Implications for exploration strategies

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ABSTRACT

Magmatic ore deposits associated with ultramafic and mafic magmatism (MODUM) include nickel sulfide deposits that are locally enriched in copper, cobalt, platinum group elements and gold, a diverse range in platinum group element deposit types, oxide- and silicate-related nickel–cobalt laterite deposits formed by weathering of ultramafic bodies, and massive and stratiform accumulations of chromite, ilmenite and vanadium-bearing magnetite. Magmatic ore deposits associated with ultramafic and mafic rocks span most of earth's history and are well represented on all continents, and in all climatic zones and physiographic regions. Currently, these deposits are estimated to account for approximately 7% of the total value of annual global metal and mineral mining. They include the world's greatest concentration of metals – the Bushveld Complex, which has an estimated total metal endowment value, representing past production and current reserves and resources, of \$US 3.6 trillion. Recent trends in exploration spending for mafic to ultramafic magmatic ore deposits compared to commodity market size and production value indicate a significant under-investment in exploration for magmatic chromite, ilmenite–vanadium and polymetallic disseminated copper–nickel–platinum group element sulfide deposits. Historically, exploration of mafic to ultramafic magmatic belts has commonly involved a narrow range of deposit models, geological environments and exploration methods. A value-based and more holistic approach to exploration for mafic to ultramafic magmatic ore deposits is proposed that captures a larger range of known mineralization styles, settings and commodities. A focus on high-value deposits providing excellent operating margins and long mine life is recommended as a starting point for new programs. However, by recognizing the full range of possible mineralization styles and understanding mineral economic thresholds, future explorers can expand the search area and methodology and increase the probability of discoveries that create value. Assuming that commodity prices continue to rise with declining average grades, current global resources hosted by mafic to ultramafic magmatic ore deposits are adequate to meet global demand for nickel, platinum group elements (PGE), chromium and vanadium for many decades to come. Despite this, the high net smelter return (NSR) value of many types of MODUM deposits provides ongoing economic motivation for both greenfields and brownfields exploration in these strategically important deposits. Furthermore, the large range in producer costs for key MODUM commodities such as nickel, copper and PGE provides significant opportunities for new projects to displace existing, higher-cost operations on the industry cost curve. The known clustering of high-value deposits within discrete magmatic belts (e.g., nickel sulfide and nickel laterite deposits) is an additional motivation for exploration investment as it allows exploration to focus early in areas of higher mineral potential. Additional incentives for MODUM exploration include the cumulative size and maturity of MODUM commodities that reduce investment risk and thereby appeal to junior explorers, mid-cap explorers and developers and major, multi-national mining companies. The economies of scales that were successfully applied to mining of large porphyry copper deposits for many decades could have a similar positive impact on a large number of advanced MODUM projects, especially polymetallic sulfide deposits capable of generating high value concentrates having significant base metal and precious metal contents.

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1. Introduction

Magmatic ore deposits associated with ultramafic to mafic magmatism (MODUM) are important contributors to current global mineral production and an essential source of several strategic, industrial metals including copper, nickel, cobalt, platinum-group elements (PGE), chromium, titanium and vanadium (e.g., [United States Geological Survey, 2013](#)). Historically, exploration and mining investment into this class of ore deposit has been led by major western producers such as Inco, Western Mining and Falconbridge and large state-owned or state-directed mining groups such as Vale, Noril'sk Nickel and the Jinchuan Group Company. In the early 2000s, hundreds of junior-sector explorers became involved in global MODUM exploration with a specific focus on greenfields projects, advanced projects in emerging mining districts and historical discoveries that were re-assessed in more detail.

For the purpose of this study, MODUM include the following subtypes of ore deposits that formed in mafic to ultramafic magmatic bodies including intrusions and lavas, or by weathering of ultramafic rocks:

- massive to disseminated copper–nickel–PGE sulfide deposits that may also contain recoverable amounts of gold and cobalt;
- massive and stratiform chromite deposits;
- massive and stratiform vanadium-bearing magnetite deposits;
- massive ilmenite deposits; and,
- nickel +/- cobalt +/-PGE laterite deposits, including saprolite, transitional and limonite subtypes, that formed during the weathering of ultramafic magmatic rocks.

This manuscript provides an independent analysis of the current value of MODUM reserves and resources in terms of both the *in situ* value of the contained metals and the estimated net smelter return (NSR) value of the mineralization. The NSR value is a common value metric for metallic mineral deposits and is typically defined as the net revenues a mine receives for its mineral concentrates after deducting transport, smelting and refining charges. An assessment of exploration spending trends is also provided in relation to total market sizes for the ore metals and minerals hosted in MODUM. Finally, a review of the geographic distribution of MODUM emphasizing magmatic provinces hosting multiple styles of MODUM leads into a discussion of optimal exploration strategies.

2. Data sources and assumptions

The reserve, resource and mine production data presented in this study are principally derived from SNL Metals and Mining's online mineral resource database ([SNL Metals and Mining, 2014a](#); [www.snl.com/Metals](#)) used here with SNL's permission. Other data sources used

include published information given in company annual reports and investor presentations, numerous web-based commodity review papers, and recent global commodity reviews provided by the United States Geological Survey, Natural Resources Canada and the Indian Geological Survey. Where resources are specifically referenced, they are inclusive of any published reserves and capture all resource (measured, indicated and inferred) and reserve (proven and probable) categories ([Canadian Institute of Mining, 2010](#)). Less than 5% of the cited resources and reserves are based on historical, non-compliant estimates. All dollar amounts refer to US dollars. All references to ounces are troy ounces. Price assumptions are based on published average metal and mineral prices for the 2013 calendar year (references provided below).

Reviews of this type are unlikely to capture 100% of the actual global mineral resource base or mine production because of the lack of published information for specific countries and certain types of mining operations such as chromite mines that are integrated with steel manufacturing businesses. However, the compiled resources described in the current study compare favorably with other, recent global reviews for the MODUM commodities in terms of total numbers of projects, resources and reserves, average grades and annual production (e.g., [United States Geological Survey Minerals Yearbooks](#) and [Mineral Commodity Summaries](#); [Indian Minerals Yearbooks](#); [Vanitec website](#); [Roskill Consulting web-based commodity reviews](#); [producer annual report global commodity reviews](#); [Johnson Matthey and CPM Group annual reviews of PGE markets](#); [Cawthorn et al., 2005](#); [Mudd, 2010](#); [Mudd et al., 2013](#); [Mudd and Jowitt, 2014](#); [Laznicka, 2010](#)).

3. Global reserves and resources

[Table 1](#) provides a statistical summary of reserve and resource information for global magmatic nickel–copper–cobalt–PGE (gold) deposits sourced from individual project data that are given in [Appendix 1](#). [Table 2](#) provides a statistical summary for magmatic chromite, vanadium and ilmenite deposits sourced from individual project data provided in [Appendix 2](#). In order to provide an equivalent basis for comparing the grade and value of the MODUM discussed in this study, both the copper equivalent and the nickel equivalent grades were calculated for each project using the factors provided in [Table 3](#). Likewise, an estimate of equivalent NSR value per tonne of resource was calculated using the standard assumptions listed in [Table 4](#). Standard assumptions were necessary to apply to the NSR calculations because of incomplete reporting of specific parameters in the NSR calculation, most notably the transport cost, recovery factors and smelter payability factors that are frequently not reported for non-western world mines and are generally not known for undeveloped resources. The assumed values for these factors are listed in [Table 4](#) and are based on typical or median values estimated from corporate annual reports on production costs. NSR value estimates are highly influenced by metal price assumptions.

The assumptions used in this study (Table 4) are based on average metal and mineral prices for the 2013 calendar year.

3.1. Nickel–copper–PGE deposits

Two principal categories of nickel deposits are included with the mafic to ultramafic group and are herein referred to as nickel–copper–PGE deposits and nickel laterite deposits, respectively. Nickel–copper–PGE deposits include nickel-rich, copper-rich and PGE-rich end members as well as true polymetallic sulfide deposits (e.g., disseminated sulfide deposits along the western margin of the Duluth Complex, Minnesota, USA; Miller et al., 2002). Nickel laterite deposits include resources with cobalt-rich and cobalt-poor resources. Although known to exist (e.g., Fifield PGE laterite deposit, New South Wales, Australia; Shi, 1995) PGE-rich laterite deposits are not considered in this study.

Table 1 summarizes basic statistics for 157 nickel–copper–PGE sulfide projects and 221 nickel laterite projects. Included in this review are projects having total resources of greater than 100,000 tonnes. Nickel–copper–PGE projects were further subdivided into nickel–copper dominant projects (>50% of in situ value represented by copper and nickel) and PGE-dominant projects (>50% of value represented by PGE). The average copper equivalent grade for all projects is 2.3%, with sulfide and laterite projects having similar average copper equivalent grades of 2.65% and 2.60%, respectively. The sulfide deposits considered here are geographically diverse but the PGE-rich deposits are concentrated in the Bushveld Complex of South Africa (Cawthorn et al., 2005). Laterite projects are dominated by deposits located in Oceania and Southeast Asia and are essentially single commodity resources with nickel accounting for an average of 94% of the contained metal value. In terms of the estimated average NSR value per tonne of resource or reserve, the laterite deposits are more valuable (\$158/tonne) than the sulfide deposits (\$127/tonne). In part, this reflects the inclusion of many sub-economic grade disseminated sulfide projects in the global resource database for sulfide projects (Appendix 1). The total value of contained metal in all nickel–copper–PGE resources considered in this review is \$9.27 trillion, including \$6.15 trillion from sulfide projects and \$3.12 trillion from laterite projects. Although global laterite resources have nearly four times the weighted average nickel grade (1.14%) of their sulfide (including both nickel and PGE deposits) counterparts (0.30%) they account for only one-third of the total contained value of global nickel–copper–PGE resources, reflecting the significant value of byproduct metals in many of the tabulated sulfide projects relative to the nickel laterite deposits (Appendix 1).

Fig. 1 is a copper equivalent grade–tonnage plot for the magmatic nickel–copper–PGE sulfide deposits and nickel laterite deposits. The sulfide projects have been classified as being nickel-rich (>50% of value associated with nickel), copper-rich (>50% of value associated with copper), PGE + gold-rich (>50% of the total value is associated with PGE + gold) or polymetallic (neither nickel, nor copper nor PGE represent >50% of the total value). The deposits are further classified as being low- (<1% copper equivalent grade), mid- (1–3% copper equivalent grade) and high-grade (>3% copper equivalent grade). High-grade deposits are dominated by nickel-rich sulfide projects and nickel laterite projects but include several polymetallic sulfide deposits. The top 15 deposits in terms of copper equivalent grades are sulfide deposits (Fig. 1, Appendix 1). The largest deposits as measured by contained copper equivalent metal are dominated by sulfide deposits (Fig. 1). It is well documented that most ore deposits tend to show an antithetic relationship between grade and tonnage (e.g., Cox and Singer, 1986). However, an important aspect of many nickel laterite and PGE-rich sulfide deposits (predominantly stratiform reef-type deposits such as the UG2 and Merensky reefs in the Bushveld Complex, South Africa; Cawthorn et al., 2005) is the maintenance of consistent grades over the full range of resource sizes (Fig. 1). In contrast, base metal-enriched Ni–Cu–PGE sulfide deposits follow the typical antithetic relationship between grade and tonnage. The implication of these trends is that

exploration for new nickel laterite and PGE-rich reef-type deposits can focus more on grade than on size provided that the host body has a reasonably large geographical extent. Many laterite deposits extend across the entire surface expression of the host ultramafic body (Golightly, 2010). Many PGE reef-type deposits occur in laterally and vertically continuous layers with the Bushveld UG2 and Merensky reefs that have been traced down dip for >2 km vertically and for tens of km along strike (Cawthorn et al., 2005).

Fig. 2 reports data for the same projects as depicted in Fig. 1 but compares NSR values to resource size. Many of the world's highest value ore occur in magmatic nickel–copper sulfide deposits (Naldrett, 2004; Laznicka, 2010). Well documented examples of high-value magmatic sulfide mineralization include massive sulfide mineralization contained in the Kambalda District komatiite-hosted nickel deposits in Western Australia (Barnes, 2006), the Talnakh ore junction in the Noril'sk–Talnakh mining district in the Taimyr region of Siberia, Russia (Naldrett et al., 1996a; Naldrett, 2004) and the Sudbury Igneous Complex, Ontario, Canada (Ames and Farrow, 2007). These deposits commonly have NSR values in excess of \$300/tonne allowing them to be profitably mined at significant depths below the earth's surface, especially for major deposits capable of supporting high production rates over a long mine life. Amongst the world's highest value metal ores are those contained in the JM reef of the Stillwater Complex, Montana, USA (Todd et al., 1982). The JM reef reserves, including both the Stillwater and East Boulder mines, have average grades equating to NSR values of approximately \$400/tonne and rivaling the value of the richest massive nickel–copper sulfide deposits (Stillwater Mining Company, 2013). In contrast, the much larger PGE-rich resources delineated in the Bushveld Complex (Merensky reef, UG2 reef and Platreef deposits) have average NSR values of ~\$125/tonne (Fig. 1, Appendix 1). Most of the known PGE-rich resources do not have high NSR values and, being associated with narrow reef-type deposits, face intrinsically high operating costs, narrow operating margins (i.e., the net cash flow from mining activities after deducting operating costs including mining, milling and general labor and administration costs) and small to moderate production volumes.

Figs. 3 and 4 compare the 157 compiled magmatic nickel–copper–PGE sulfide deposits discussed above to data for 842 non-MODUM copper deposits including porphyry copper deposits, sediment-hosted deposits, volcanogenic massive sulfide deposits, skarn deposits and hydrothermal deposits (data sourced from SNL Metals and Mining, 2014a). In comparison to other types of copper deposits, MODUM copper–nickel–PGE sulfide deposits and sediment-hosted copper–cobalt sulfide deposits (Hitzman et al., 2005) dominate the highest grade and highest NSR value populations (Figs. 3 and 4). Porphyry copper deposits account for most of the low-grade deposits but also account for the largest resources with several projects having resources and reserves in excess of ten billion tonnes (Fig. 3; see also Mudd et al., 2013).

The successful implementation of large scale mining of giant porphyry copper deposits in the western cordilleran regions of North and South America has allowed profitable mining of many low-grade deposits (Sillitoe and Perello, 2005). Despite the presence of similar size and commonly higher-grade MODUM-related copper–nickel–PGE projects, only a few deposits such as Mount Keith (BHP Billiton, Western Australia) and the Platreef (Anglo American Platinum, South Africa) have had similar bulk mining methods successfully applied. Comparing NSR values and deposit size (Fig. 4), MODUM resources and sediment-hosted copper–cobalt deposits account for the majority of high NSR value deposits (i.e., >\$200/tonne). PGE-rich MODUM are distinguished from other MODUM by their relatively large resource sizes and moderate to high NSR values.

Fig. 5 illustrates the regional distribution of MODUM-related copper, nickel, PGE and cobalt resources. Global nickel resources are overwhelmingly associated with MODUM. Nickel resources associated with sulfide deposits show a fairly even spread between Africa, Eurasia and North America with less than 10% of these resources occurring in

	Cu value (\$US M)	Ni value (\$US M)	Co value (\$US M)	Pd value (\$US M)	Pt value (\$US M)	Rh value (\$US M)	Au value (\$US M)	Ag value (\$US M)	Total value (\$US M)	Cu eq. grade (%)	Ni eq. grade (%)	NSR value (\$/t)
# Deposits - all types	114	335	156	134	134	57	94	5	378	378	378	378
Total	787,718	4,488,205	294,590	1,026,537	2,322,078	148,261	198,718	478	9,266,585	-	-	-
Minimum	1	0	9	0	2	1	0	0	58	0.17	0.08	4.43
Maximum	236,339	255,793	27,937	209,961	140,984	10,420	23,552	303	849,616	11.78	5.75	566
Median	1,077	5,465	562	0	3,600	1,193	349	39	7,829	2.40	1.17	139
Average	6,910	13,398	1,888	2,716	17,459	2,601	1,840	80	24,515	2.62	1.28	145
# Ni-Cu sulfide deposits	66	66	31	45	45	2	45	5	68	68	68	68
Total	665,664	1,252,009	102,105	334,858	304,408	2,471	66,226	478	2,728,220	-	-	-
Minimum	13	0	15	0	2	1	0	8	58	0.28	0.13	10.1
Maximum	236,339	255,793	27,937	209,961	123,061	2,471	23,552	303	849,616	11.78	5.75	566
Median	1,442	4,494	764	58	550	1,236	70	70	6,493	1.58	0.77	70.4
Average	10,086	18,687	3,294	4,924	6,765	1,236	1,472	96	40,121	2.91	1.42	129
# PGE deposits	48	48	1	89	88	55	63	0	89	89	89	89
Total	122,054	310,549	38	691,679	2,017,670	145,790	132,491	0	3,420,271	-	-	-
Minimum	1	17	0	0	101	15	12	0	130	0.17	0.08	4.43
Maximum	56,384	58,631	38	55,678	140,984	10,420	22,352	0	318,509	6.86	3.35	378
Median	643	3,098	<1	4,097	11,503	1,193	635	0	18,613	2.46	1.20	126
Average	2,543	6,607	<1	7,772	22,928	2,651	2,103	0	38,430	2.45	1.19	126
# Laterite deposits	0	221	124	0	0	0	0	0	221	221	221	221
Total	0	2,925,647	192,447	0	0	0	0	0	3,118,094	-	-	-
Minimum	0	63	9	0	0	0	0	0	75	0.78	0.38	43.8
Maximum	0	125,320	18,036	0	0	0	0	0	125,320	5.59	2.73	345
Median	0	6,591	533	0	0	0	0	0	6,877	2.42	1.18	147
Average	0	13,238	1,552	0	0	0	0	0	14,109	2.60	1.27	158

Table 2
Statistical summary of global magmatic oxide resources and values. See Appendix 2 for the individual project source data. Weighted average determined for grade using the resource or reserve tonnage weighting factor.

	Chromite resources and reserves		V ₂ O ₅ resources			V ₂ O ₅ reserves		
	Resources (t)	Reserves (t)	Tonnage (t)	Grade (%)	Contained (t)	Tonnage (t)	Grade (%)	Contained (t)
# projects	65	31	49	49	49	10	10	10
Total	1,364,186,243	321,140,778	16,364,124,000	–	39,875,852	2,648,364,000	–	6,905,478
Minimum	113,730	69,000	3,200,000	0.050	5953	13,851,000	0.140	82,016
Maximum	187,258,320	85,279,800	3,943,800,000	1.740	5,915,700	1,994,360,000	1.740	2,792,104
Median	6,171,200	4,183,900	99,000,000	0.420	448,840	48,410,000	0.560	322,441
Average	20,987,481	10,359,380	333,961,714	0.464	813,793	264,836,400	0.697	690,548
Weighted average	–	–	–	0.244	–	–	0.261	–
	TiO ₂ resources			TiO ₂ reserves				
	Tonnage (t)	Grade (%)	Ilmenite ^a contained (t)	Tonnage (t)	Grade (%)	Ilmenite ^a contained (t)		
# projects	47	47	47	6	6	5		
Total	19,814,646,000	–	2,258,813,492	564,690,000	–	114,254,909		
Minimum	3,200,000	1.83	1,153,505	12,470,000	5.55	2,496,206		
Maximum	4,711,000,000	33.60	209,587,665	229,000,000	15.69	60,018,882		
Median	113,400,000	9.05	19,031,953	53,860,000	10.35	11,830,056		
Average	421,588,213	10.46	48,059,862	94,115,000	10.66	22,850,982		
Weighted average	–	6.00	–	–	11.39	–		
	Chromite resources		V ₂ O ₅ resources	TiO ₂ resources	V ₂ O ₅ + TiO ₂ resources ^b			
	Value (\$US M)		Value (\$US M)	Value (\$US M) ^a	Cu eq. grade (%) ^c		NSR value (\$/t)	
# projects	65		49	47	60		60	
Total	954,930		580,213	451,763	n/a		n/a	
Minimum	80		87	230.70	0.10		1.16	
Maximum	131,081		86,076	41,917.53	3.46		177.28	
Median	4,320		6,531	3806.39	1.07		54.16	
Average	14,691		11,841	9611.97	1.18		59.94	
Weighted average	–		–	–	–		–	

^a TiO₂ resources expressed as ilmenite assuming stoichiometric ilmenite composition.

^b Equivalent grades and NSR values determined for all resources containing either V₂O₅ or TiO₂ where deposits containing both have equivalent grades and values summed.

^c Cu equivalent grade estimated using factors provided in Table 3.

other regions (Fig. 5a). In contrast, nickel laterite resources are dominated by the Oceania and Southeast Asia regions with significant but fewer resources occurring in South America (mainly Brazil), Africa and Central America (Fig. 5b). Taken together, the world's known nickel sulfide and nickel laterite resources are relatively evenly distributed (Fig. 5c) and integrated smelting and refining businesses and/or laterite hydrometallurgical or pyrometallurgical plants have been constructed on most continents. Copper resources associated with MODUM are dominated by copper–nickel–PGE sulfide projects in Africa, Eurasia and North America (Fig. 5d). South Africa (Bushveld Complex) and Zimbabwe (Great Dyke) account for a majority of global PGE resources but the Noril'sk Nickel Company has amassed the world's largest palladium resource of ~300 million ounces from its Taimyr operations in the Noril'sk–Talnakh ore district in Russia (Appendix 1). Global cobalt resources associated with MODUM are dominated by laterite projects in Australia, New Caledonia and southeast Asia but include important contributions from North American magmatic nickel–copper sulfide

deposits including the producing Sudbury and Voisey's Bay nickel sulfide deposits (Naldrett, 2004) and several large but undeveloped projects such as Wellgreen in Canada's Yukon Territory (Simpson, 2014) and several disseminated sulfide deposits in the Duluth Complex, Minnesota, USA (Miller et al., 2002).

3.2. Chromite, vanadium and titanium deposits

MODUM oxide deposits include chromite deposits, titanium-rich magnetite–ilmenite and ilmenite deposits and vanadium-bearing magnetite deposits. Table 2 provides summary statistics for 125 oxide MODUM deposits including 65 chromite deposits, 49 vanadium ± magnetite ± ilmenite deposits and 11 ilmenite deposits listed in Appendix 2. A total of 47 of the oxide MODUM deposits considered report TiO₂ resources. Grade data is provided for vanadium (% V₂O₅) and ilmenite (% TiO₂) deposits but not for chromite deposits. There is very limited public disclosure of chromite resource grades, mineral composition and retail

Table 3
Copper equivalent grade factors. Based on 2013 average metal price assumptions shown.

	Cu (%)	Ni (%)	Co (%)	Pt (g/t)	Pd (g/t)	Rh (g/t)	Au (g/t)
Price unit	Tonne	Tonne	Tonne	Troy ounce	Troy ounce	Troy ounce	Tonne
Equivalency	1.00	2.049	3.613	0.654	0.319	0.469	0.620
Price (\$US)	7,322	15,007	26,455	1,490	727	1,067	1,411
	Ag (g/t)	Chromite (t)	TiO ₂ (%) ^a	V ₂ O ₅ (%)	Pb (%)	Zn (%)	Mo (%) ^b
Price unit	Troy ounce	Tonne	Tonne	Tonne	Tonne	Tonne	Tonne
Equivalency	0.010	n/a	0.052	1.987	0.261	0.261	2.58
Price (\$US)	23.8	700.0	200	14,550	1,908	1,910	28,307

^a Tonne ilmenite estimated from TiO₂ grade and assuming stoichiometric ilmenite composition.

^b Molybdenum price is based on MoO₃ content but resource grade is reported as % elemental molybdenum.

Table 4

Net smelter return (NSR) value estimation factors and equations for the different deposit types considered in this paper.

Commodity	Recovery	Payability ^a	Price unit	Price (\$US)	Grade unit	NSR factor	Transport (\$US)
Copper	85.0%	90.0%	Tonne	7,322	%	56.02	5.00
Nickel (sulfide) ^b	70.0%	90.0%	Tonne	15,007	%	94.54	5.00
Nickel (laterite)	95.0%	90.0%	Tonne	15,007	%	128.31	5.00
Cobalt (sulfide)	70.0%	50.0%	Tonne	26,455	%	92.59	5.00
Cobalt (laterite)	95.0%	90.0%	Tonne	26,455	%	226.19	5.00
Platinum	85.0%	90.0%	Troy ounce	1,490	g/t	36.65	5.00
Palladium	85.0%	90.0%	Troy ounce	727	g/t	17.88	5.00
Rhodium	85.0%	80.0%	Troy ounce	1,067	g/t	23.33	5.00
Gold	85.0%	90.0%	Troy ounce	1,411	g/t	34.71	5.00
Silver	85.0%	80.0%	Troy ounce	23.8	g/t	0.52	5.00
Chromite	90.0%	90.0%	Tonne	700	Tonne	567.00	5.00
Ilmenite	90.0%	90.0%	Tonne	200	% TiO ₂	3.08	5.00
Vanadium	90.0%	80.0%	Pound V ₂ O ₅	6.60	% V ₂ O ₅	104.76	5.00
Lead	85.0%	90.0%	Tonne	1,908	%	14.59	5.00
Zinc	85.0%	90.0%	Tonne	1,910	%	14.61	5.00
Molybdenum	85.0%	90.0%	Tonne	28,307	%	144.34	5.00

NSR equation for Ni–Cu sulfide and PGE deposits:

$$\text{NSR value (\$US per tonne of ore)} = (\text{Cu} * 56.02 + \text{Ni} * 94.54 + \text{Co} * 92.59 + \text{Au} * 34.71 + \text{Pt} * 36.65 + \text{Pd} * 17.88 + \text{Rh} * 23.33 + \text{Ag} * 0.52) - 5.00.$$
NSR equation for Ni(Co) laterite deposits:

$$\text{NSR value (\$US per tonne of ore)} = (\text{Ni} * 128.31 + \text{Co} * 226.19) - 5.00.$$
NSR equation for magmatic Fe–Ti–V deposits:

$$\text{NSR value (\$US per tonne of ore)} = (\text{TiO}_2 * 3.08 + \text{V}_2\text{O}_5 * 104.76) - 5.00.$$
NSR equation for Cu deposits that are not related to mafic–ultramafic rocks (non-MODUM):

$$\text{NSR value (\$US per tonne of ore)} = (\text{Cu} * 56.02 + \text{Co} * 92.59 + \text{Au} * 34.71 + \text{Pt} * 36.65 + \text{Pd} * 17.88 + \text{Rh} * 23.33 + \text{Ag} * 0.52 + \text{Pb} * 14.59 + \text{Zn} * 14.61 + \text{Mo} * 144.34) - 5.00.$$
^a Assumes on site milling and shipping of concentrate to commercial smelter, furnace or hydrometallurgical plant.^b Assumes an average 20% of nickel for Cu–Ni–PGE sulfide resources is unrecoverable silicate nickel (actual silicate nickel contents are highly variable but are not known for most of the deposits considered).

pricing arrangements, which are defined in confidential purchase contracts between producers and steel manufacturers or their proxies from the purchaser's federal government (Papp and Lipin, 2006). Global resource values for chromite projects are therefore based on an assumed, industry-wide average value (\$700/tonne) for chromite concentrate regardless of the actual resource grades and chromite mineral compositions in the deposits.

The global chromite resource base estimated here and discussed further in recent United States Geological Survey annual commodity mineral survey reports is only a fraction of the world's known chromite resources. This disparity reflects the lack of published grade and tonnage data for many of the world's integrated chromite mining and steel manufacturing businesses and the complexity of chromite concentrate valuation methods. With these limitations in mind, the published

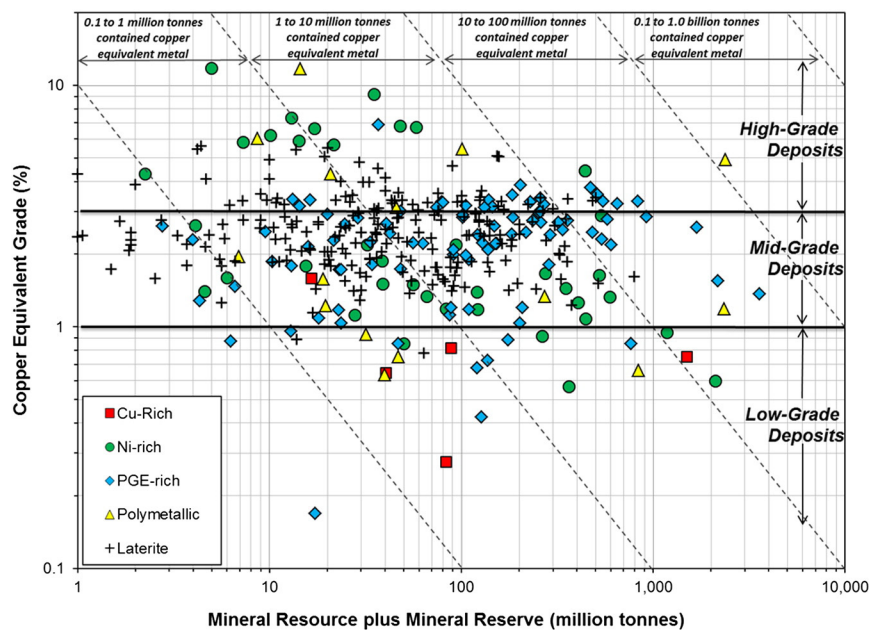


Fig. 1. Copper equivalent grade versus combined reserves and resources for magmatic nickel–copper–PGE projects. Data are derived from Appendix 1 and are primarily sourced from SNL Metals and Mining (2014a). Deposit classes shown in the legend are defined as follows: Cu-rich MODUM are those in which copper represents >50% of the total contained metal value; Ni-rich MODUM are those in which nickel represents >50% of the total contained metal value; PGE-rich MODUM are those in which PGE + Au represents >50% of the total contained metal value; Polymetallic MODUM are those in which neither Cu, Ni or PGE represent more than 50% of the contained metal value. Grade classifications are defined as follows: low grade – <1% copper equivalent grade; mid grade – 1–3% copper equivalent grade; high grade – >3% copper equivalent grade. Equivalent grades are estimated using the factors provided in Table 3. Note that using 2014 metal price assumptions, the nickel equivalent grade can be estimated as being approximately 50% of the copper equivalent grade.

global chromite resources and reserves considered in Table 2 and documented in detail in Appendix 2 total 1.69 billion tonnes of chromite. Current annual consumption rates are estimated to be approximately 26 million tonnes (United States Geological Survey, 2014a). Accordingly the known chromite reserves and resources, which are clearly an underestimate of the world's actual chromite resources, represent ~65 years of global demand at 0% per annum growth and 30 years of global demand at 5% per annum growth. These resources show a roughly linear size distribution ranging from small resources with <100,000 tonnes of chromite ore to giant resources in excess of 100 million tonnes of chromite ore (Fig. 6). The average size of the documented chromite resources is approximately 21 million tonnes of chromite ore. Most chromite resources occur in podiform deposits in ophiolite complexes (e.g., deposits in the Philippines, Cyprus and Greece) or in stratiform deposits in the ultramafic portions of large layered intrusions such as the giant stratiform chromite resources of the Bushveld Complex (Papp and Lipin, 2006; Cawthorn et al., 2005). These figures suggest that there is no imminent shortage of chromite resources. However, as with any mineral commodity, fluctuations in commodity prices relating to falling demand or slowing demand growth (in this case, relating to global chromium steel demand) can render some of the current mine supply sub-economic.

Global vanadium resources associated with MODUM are largely confined to ferrogabbroic intrusions or ferrogabbroic units in layered mafic (ultramafic) complexes. By far the largest resources are hosted in the Main Zone of the Bushveld Complex (Cawthorn et al., 2005) but significant and expanding resources are also documented in the Panzhihua Complex in Sichuan Province, China (Pang et al., 2010; Bai et al., 2012) and the Windimurra Complex, Australia (Ivanic et al., 2012; Atlantic Ltd., 2015). Most of these resources feature vanadium-rich magnetite and many also contain intergrown or spatially associated ilmenite mineralization. Typical vanadium grades for these resources expressed as V_2O_5 are ~0.5% but individual deposit grades range from <0.1% for deposits in which vanadium is a byproduct metal to ~1.7% for primary vanadium deposits (Fig. 7). With global V_2O_5 consumption estimated at ~130,000 tonnes in 2013 (United States Geological Survey, 2014a) the current global MODUM-related V_2O_5 resources and reserves estimated

at ~40 million tonnes is equivalent to greater than 300 years of required annual mine supply based on current demand levels. Even if only a fraction of these resources prove to be sufficiently profitable to extract, MODUM resources alone should be more than adequate to meet global demand for many decades.

Most of the world's titanium mine production, primarily used in the production of synthetic rutile for pigment manufacturing, is sourced from heavy mineral sand deposits (Force, 1991; United States Geological Survey, 2013). MODUM-related bedrock ilmenite deposits of sufficient grade and quality for profitable extraction are very limited in number. Primary magmatic ilmenite deposits are most commonly associated with anorthositic intrusions including the Lac Tio deposit in Quebec (Corriveau et al., 2007) and the Telnes deposit in Norway (Eilu, 2012). To be profitable, bedrock ilmenite mines require sufficient size and grade to support the construction of on-site or nearby processing plants that typically employ thermo-chemical metallurgical processes involving either chlorine or sulfuric acid (Force, 1991). Many of the reported ilmenite resources relate to vanadium-bearing magnetite-ilmenite deposits where intergrown magnetite and ilmenite is concentrated and then smelted to generate saleable pig iron, vanadium slag and titanium slag. Reported TiO_2 grades for the documented resources considered in this study range from <2% for vanadium-rich resources to 33.6% for the richest anorthosite-related primary ilmenite deposits (Fig. 8). Global ilmenite resources associated with MODUM are estimated at ~2.26 billion tonnes. This is a small fraction of total global TiO_2 (ilmenite-rutile-leucosene) resources that are dominated by mineral sand deposits. Current annual demand is assessed at ~13 million tonnes per annum (United States Geological Survey, 2014b). At this level, MODUM TiO_2 resources alone would be sufficient to meet industrial demand for nearly 175 years.

Fig. 9 plots estimated NSR values and tonnages for vanadium and ilmenite MODUM resources with the data subdivided into magnetite resources containing vanadium and iron, ilmenite resources containing TiO_2 and magnetite-ilmenite resources containing vanadium, TiO_2 and iron. Although none of the oxide projects attain the high copper equivalent grades seen in the highest-grade MODUM projects (Fig. 1), several oxide projects have NSR values in the range of \$50–\$100/tonne and a few projects have NSR values in excess of \$100/tonne (Fig. 9). At these

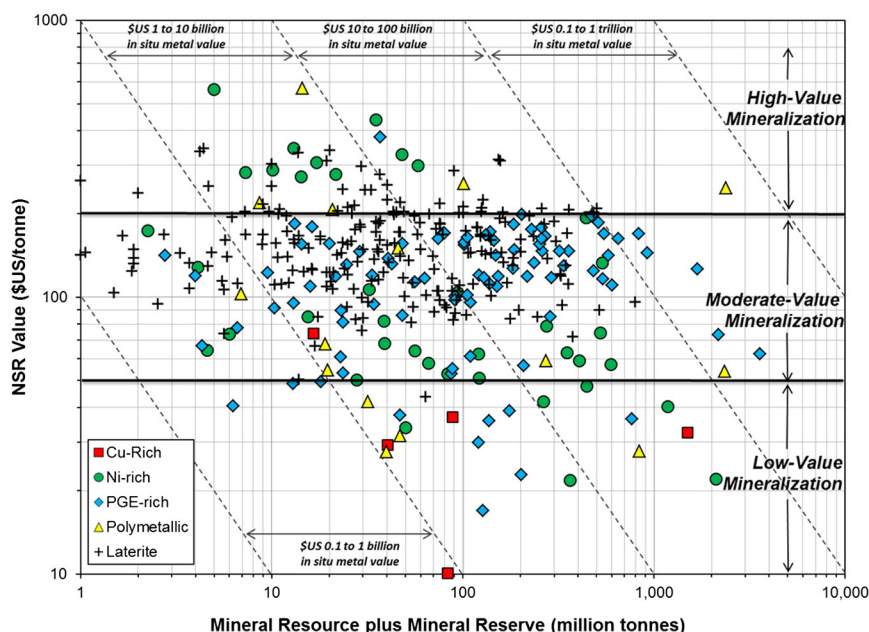


Fig. 2. NSR value versus combined reserves and resources for magmatic nickel–copper–PGE projects. Data are derived from Appendix 1 and are primarily sourced from SNL Metals and Mining (2014a). NSR values are estimated using the assumptions and methods listed in Table 4. Deposit NSR estimates are provided in Appendix 1. Deposit classes shown in the legend are the same as those described in Fig. 1. Mineralization value classifications are defined as follows: low value – NSR < \$50/tonne; moderate value – NSR between \$50/tonne and \$200/tonne; high value – NSR > \$200/tonne.

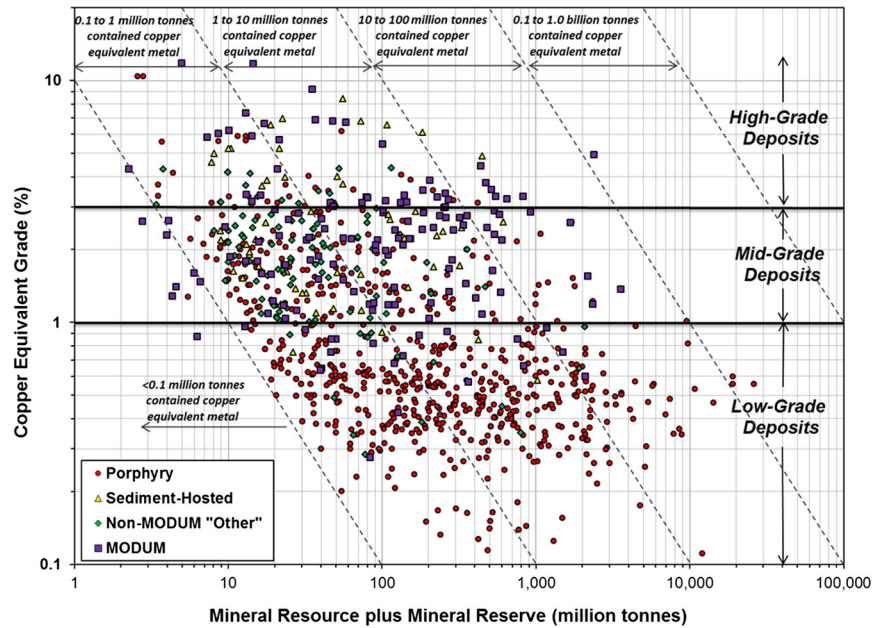


Fig. 3. Copper equivalent grade versus combined reserves and resources for magmatic nickel–copper–PGE projects and other types of copper deposits. Data for other copper deposits are sourced from *SNL Metals and Mining* (2014a) and include information for 842 deposits having greater than one million tonnes of total resources and reserves. MODUM deposits are grouped from the categorized data shown in *Figs. 1 and 2*.

values, and assuming some form of bulk mining method is employed, undeveloped oxide MODUM resources appear to hold substantial value. In fact, most operating magmatic oxide mines are large-scale and have low operating costs. This is particularly the case for the large tonnage, moderate grade magnetite–ilmenite deposits that produce saleable iron, vanadium and titanium products (e.g., Pangang Group Ltd.'s Phanzhihua mine, Sichuan Province, China). MODUM deposits having ilmenite as the primary or sole payable commodity require extremely high grades (>25%) and purity (i.e., near-stoichiometric

ilmenite with very low abundances of deleterious minerals) to be considered for development.

Fig. 10 illustrates the global distribution of the oxide MODUM projects discussed above. Global chromite resources (*Fig. 10a*) are currently dominated by projects in southern Africa (Bushveld Complex and lesser resources in the Great Dyke; *Cawthorn et al., 2005*), Eurasia (especially Kazakhstan and India; *Indian Minerals Yearbook, 2012*) and North America where recently discovered deposits from the "Ring of Fire" district in northwestern Ontario are currently at the advanced

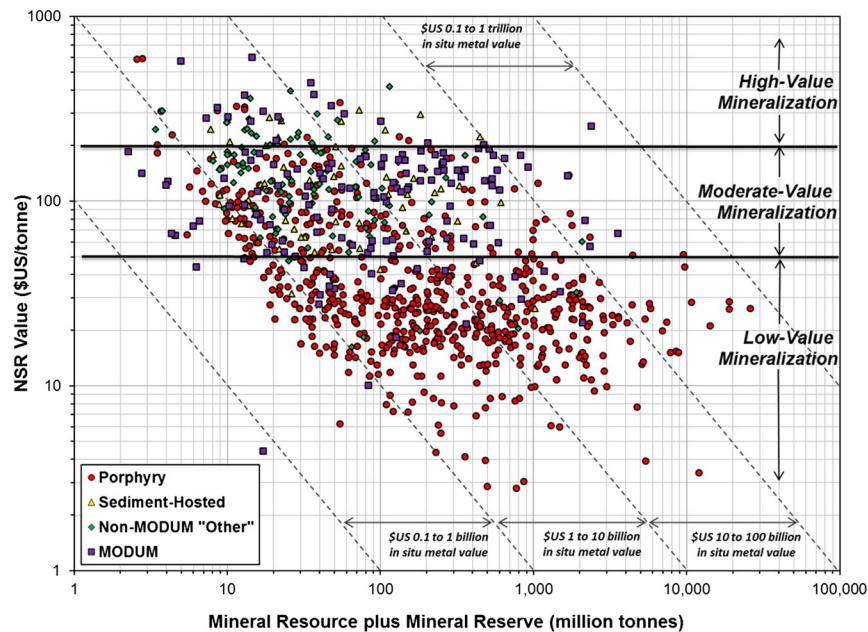


Fig. 4. NSR value versus combined reserves and resources for magmatic nickel–copper–PGE projects and other types of copper deposits. Data for other copper deposits are sourced from *SNL Metals and Mining* (2014a) and include information for 842 deposits having greater than one million tonnes of total resources and reserves. MODUM deposits are grouped from the categorized data shown in *Figs. 1 and 2*.

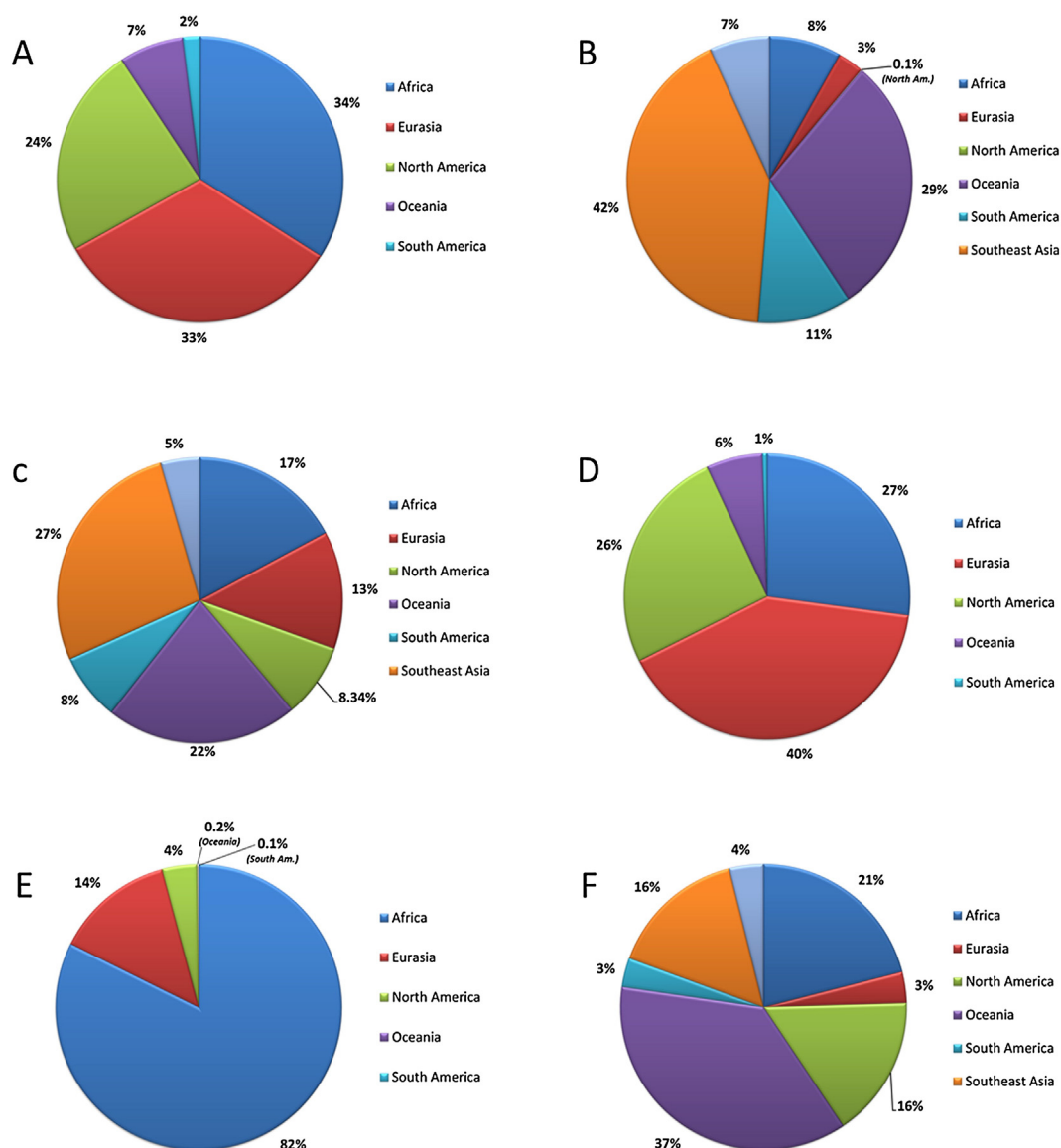


Fig. 5. Geographic split of global nickel resources contained in copper–nickel–PGE (sulfide) projects. All charts show the percentage of total contained metal in reserves and resources for each region shown. Where a region is not shown, there are no resources or reserves reported. A. Data for nickel for sulfide projects only. B. Data for nickel for laterite projects only. C. Data for nickel for combined sulfide and laterite projects. D. Data for copper for sulfide projects only. E. Data for platinum for sulfide projects only. F. Data for palladium for sulfide projects only. Data are based on the information provided in Appendix 1 and primarily sourced from *SNL Metals and Mining (2014a)*.

exploration stage (Laarman, 2014). Global vanadium (Fig. 10b) and ilmenite (Fig. 10c) resources hosted by mafic and ultramafic magmatic bodies are relatively equally distributed between Africa (mostly Bushveld Complex projects), Eurasia, North America and Oceania.

4. Global production

The relative size of each commodity market can be measured from annual mine production that in most cases approximates global demand. Table 5 provides estimates of the amount and value of mine production for MODUM commodities including MODUM and non-MODUM deposits. Fig. 11 plots the total value of 2013 mine production for MODUM commodities including production data for both MODUM and non-MODUM deposits. Fig. 12 plots the total value of 2013 mine production for MODUM commodities using data for MODUM only. The total value of global metal and mineral (excluding fossil fuels) production in 2013 is estimated at approximately \$1 trillion dollars (United States Geological Survey, 2013), of which \$73 billion was sourced from

MODUM. 2013 global copper mine production from all sources is valued at \$132 billion, of which \$4.6 billion or 3.5% is mined from MODUM (Fig. 12). Gold production in 2013 has a similar value of \$126 billion, of which ~\$700 million or 0.6% is sourced from MODUM (Fig. 12). The remaining MODUM commodity markets – nickel, PGE, chromite, vanadium and ilmenite, are much smaller than those of copper and gold. These are the commodities for which MODUM are either the principal source or are one of the primary sources. Using the information presented in Table 5 and referring to mine production data sourced from both *SNL Metals and Mining (2014a)* and the United States Geological Survey mineral commodity summaries it is estimated that 2013 MODUM mine production represents the following percentages of global mine output: nickel – 100%; chromite – 100%; PGE – 100%; vanadium – 85%; ilmenite – 31%; copper – 3.5%; gold – 0.6%. These estimates do not capture placer mining, artisanal mining or poorly documented or undisclosed byproduct mining outputs that may be significant for some commodities (e.g., PGE). Of the MODUM commodities, nickel (\$33 billion), chromite (\$18 billion) and PGE (\$14 billion) account for most of the

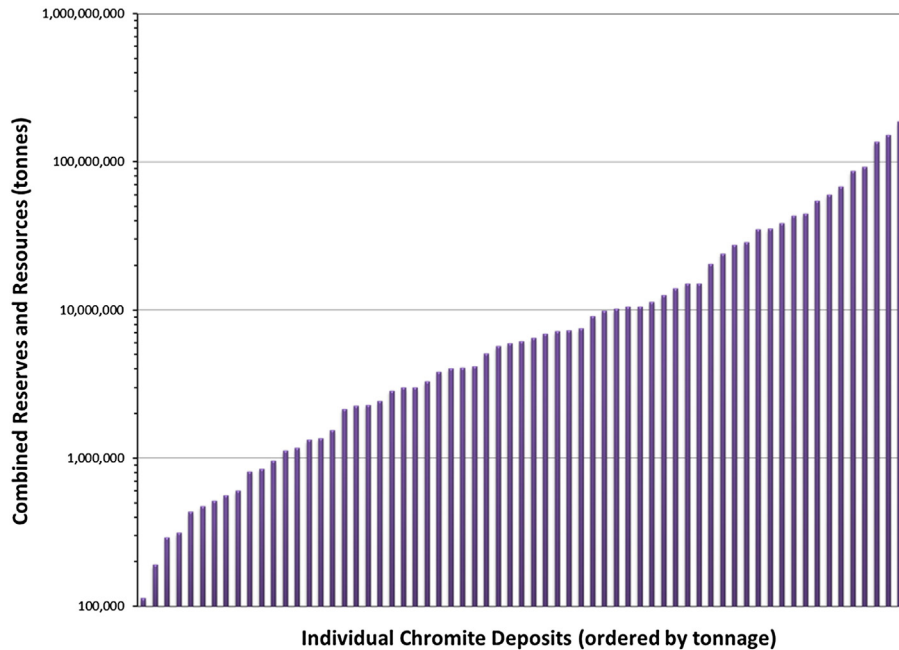


Fig. 6. Distribution of global chromite deposit tonnages based on combined resources and reserves. The deposits are listed in order of increasing size (tonnage). Data are based on the information provided in Appendix 2 and primarily sourced from [SNL Metals and Mining \(2014a\)](#). A total of 65 chromite deposits are considered.

value of mine production. The value of 2013 MODUM-related vanadium mine production (\$4.2 billion) is approximately the same as copper mine production sourced from MODUM (\$4.6 billion; [Fig. 12](#)).

Actual 2012 global nickel production figures were used in lieu of the estimated 2013 production figures to assess the regional distribution of mine production for the most important MODUM commodities ([Fig. 13](#)). Nickel mine production is dominated by Oceania (26%), Southeast Asia (24%), Eurasia (19%) and North America (14%). Nickel mine production from South America (8%; mainly from Brazil) has grown significantly in recent years and is expected to continue to gain market share as additional mid- to high-grade laterite projects come on line. Copper mine production sourced from MODUM is dominated by Eurasia (61%) and North America (32%), reflecting the strong geographic bias of major copper-rich magmatic sulfide resources to the

northern hemisphere. In contrast, platinum mine production is almost exclusively sourced from southern Africa (80%) with a majority of production from Bushveld Complex mines in South Africa but with increasing production from the Great Dyke operations in Zimbabwe. Palladium, which is a common byproduct of copper–nickel–PGE mining operations, shows more diversity in supply with approximately equal mine production from Africa (45%) and Eurasia (40%; mainly from the Noril'sk Talnakh operations) and smaller but significant production from North America (15%).

Global mine production from oxide MODUM projects is much more limited in terms of both the number of operations and their geographic diversity (Appendix 2). For chromite, a majority of mine production is sourced from South Africa, Kazakhstan and India ([United States Geological Survey, 2014a](#)). For vanadium, MODUM-related production is dominated by China and South Africa, although significant new

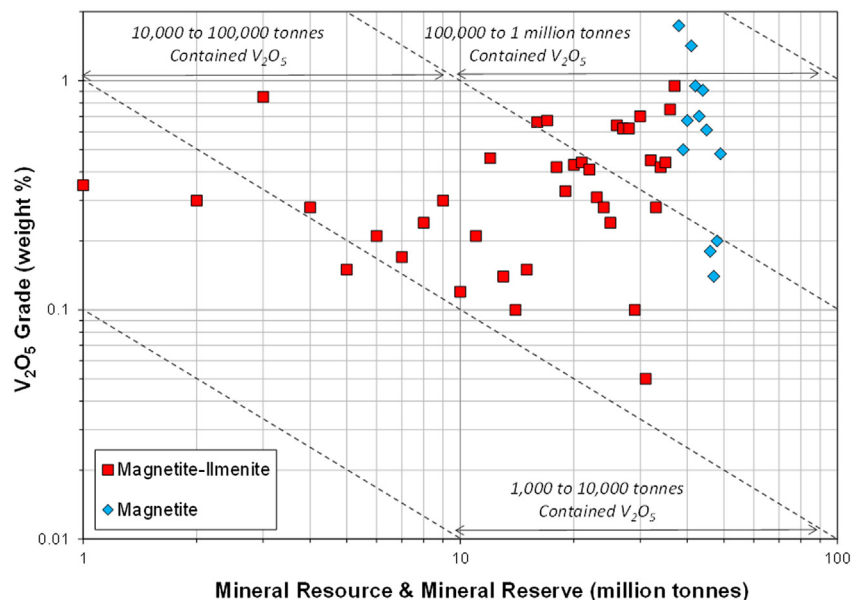


Fig. 7. Grade versus combined reserves and resources for global MODUM-related vanadium deposits. Data are based on the information provided in Appendix 2 and primarily sourced from [SNL Metals and Mining \(2014a\)](#).

production is developing in Western Australia (Windimurra Complex; <http://atlanticltd.com.au/>) and Brazil (Maracas Mine; <http://www.largoresources.com/>). For primary ilmenite, the only significant bedrock mine production is from China, Canada and Norway. The lack of supply diversity for MODUM vanadium and titanium mines is not surprising given the small size of global vanadium and titanium markets.

Although global chromite markets are much larger than those for vanadium and ilmenite, MODUM-related chromite mine production shows a similar lack of geographic diversity. This situation is likely a reflection of the significant economic and technological barriers to new mine development for chromite and the fact that many chromite mines are part of an integrated steel business. However, quality new chromite discoveries including remote deposits such as those identified in the "Ring of Fire" district in northwestern Ontario, Canada (Laarman, 2014) stand a good chance of being developed given the high chromium content of the ore, the significant size of the known resources and the presence of a large North American steel industry. The lack of diversification in global chromite mine supply and the strategic importance of chromite for many steel manufacturers, particularly in North America, will continue to provide opportunities for new chromite resources to be developed.

5. Global exploration

Another important aspect of MODUM-related commodity markets is the trend in related global annual exploration spending by mining and exploration companies. Although difficult to accurately predict for the smaller commodity markets such as ilmenite and vanadium, robust estimates of global nickel ($\pm$ copper) and PGE exploration investments can be deduced from corporate annual reports and annual information filings for mining and exploration companies whose businesses are tied to these metals. The data presented in this section are principally sourced from recent *SNL Metals and Mining* (2014b) augmented by independent research on published exploration spending in 2013. Table 6 provides summary statistics for the individual country exploration spending estimates (*SNL Metals and Mining*, 2014b) for Ni–Cu sulfide and PGE projects with reference to exploration spending for gold, copper and diamond projects. Table 7 compares 2013 exploration spending to the estimated value of 2013 mine production. Fig. 14 illustrates the geographic split in exploration spending for nickel and PGE projects. Resource conversion drilling projects are sometimes

excluded from corporate exploration expenditure reporting so the figures presented may underestimate actual exploration spending.

Global exploration spending for MODUM nickel projects was dominated by countries from the Oceania region (\$199 million), Eurasia (\$139 million) and North America (\$103 million) with smaller but significant exploration spending in Southeast Asia, South America and Africa (Fig. 14). For PGE, exploration spending in 2013 was dominated by African projects (\$78 million), the majority of which are located in the Bushveld Complex (Fig. 14). Despite significant PGE resources and several advanced PGE exploration projects in Scandinavia and Russia, PGE spending in Eurasia was quite limited in 2013 (\$32 million). This likely reflects both the general decline in junior sector financing for exploration in 2013 (especially for PGE) and the fact that PGE are commonly not the primary commodity for Ni–Cu–PGE exploration projects even where they represent a significant percentage of the contained metal value in the targeted mineralization. Global exploration spending on PGE has declined significantly from historical peaks of ~\$300 million in the mid-2000s to the estimated 2013 total global exploration spending of \$120 million (Table 6). Most of the decline can be ascribed to recent, steep reductions in platinum exploration investment in South Africa following a major exploration boom during the mid-2000s. That boom was partly triggered by the South African government's Black Empowerment (BE) legislation requiring a minimum 26% ownership of mining assets by Historically Disadvantaged South Africans. The BE legislation prompted most of the South African PGE miners to update their resource and reserve estimates in order to maintain compliance with the South Africa Mining Act and provide a better basis for long-term strategic planning. More recently the South African PGE mining industry experienced a significant reduction in profits in response to rising operating costs and lower than expected platinum demand and prices, despite production shortfalls related to the 2014 PGE miner's strike action.

In order to evaluate the relative strength of exploration investment for MODUM nickel ($\pm$ copper) projects, including sulfide and laterite projects, the annual spend by region was compared to the value of mine production in that region (Fig. 15). The key exploration and production regions show a healthy range in the proportion of exploration spending to the production value of 1–3% (Fig. 15). This range is generally in line with that seen in other commodities such as copper and gold (Table 7). In 2013, the value of global copper production was approximately \$132 billion and exploration spending for copper

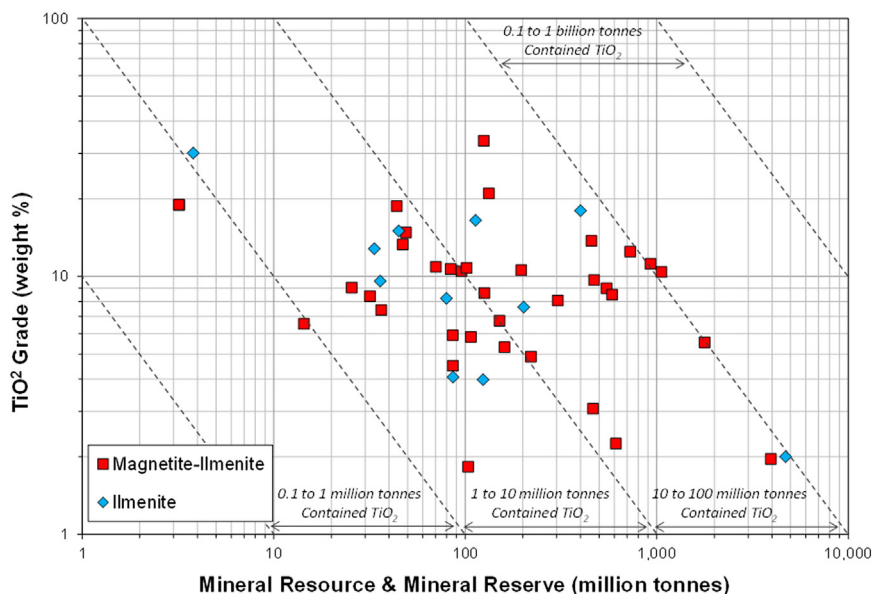


Fig. 8. Grade-tonnage plot for global MODUM-related TiO_2 resources and reserves. Data are based on the information provided in Appendix 2 and primarily sourced from *SNL Metals and Mining* (2014a).

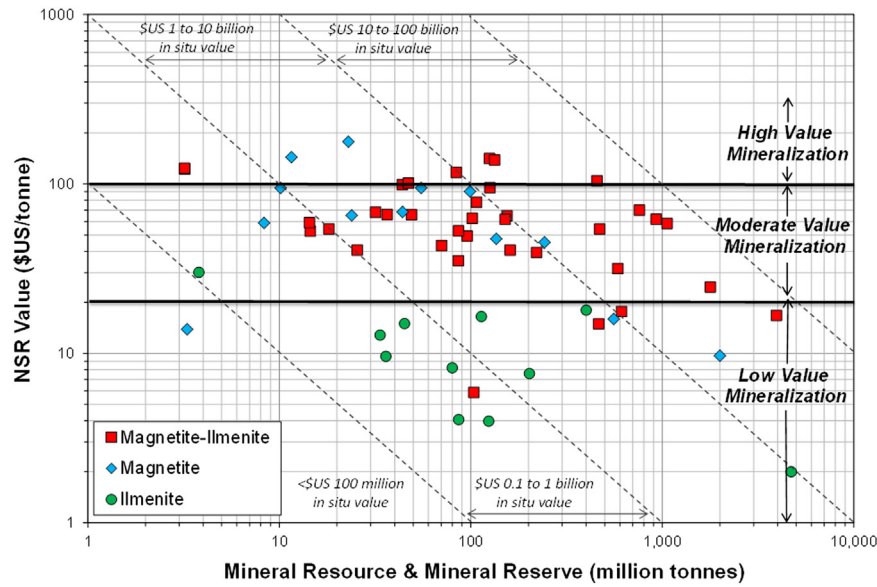


Fig. 9. NSR value versus combined reserves and resources for MODUM-related magnetite and/or ilmenite deposits. NSR values are estimated using the assumptions and methods listed in Table 4. Data are based on the information provided in Appendix 2 and primarily sourced from SNL Metals and Mining (2014a). Mineralization value classifications are defined as follows: low value – NSR < \$20/tonne; moderate value – NSR between \$20/tonne and \$100/tonne; high value – NSR > \$100/tonne.

projects was ~\$3.5 billion or 2.6% of the value of copper mine production worldwide (Table 7). In the case of gold, the value of 2013 mine production is estimated at \$126 billion whereas exploration spending was ~\$6.2 billion or 5.2% of the value of global mine production (Table 7). These figures are a direct reflection of the overall health of global

commodity markets with exploration spending generally lagging slightly behind peaks in demand and price for most commodities.

Relative to gold and copper, commodities most strongly associated with MODUM (nickel, PGE) show less diversification in terms of the number of countries reporting active exploration projects in 2013

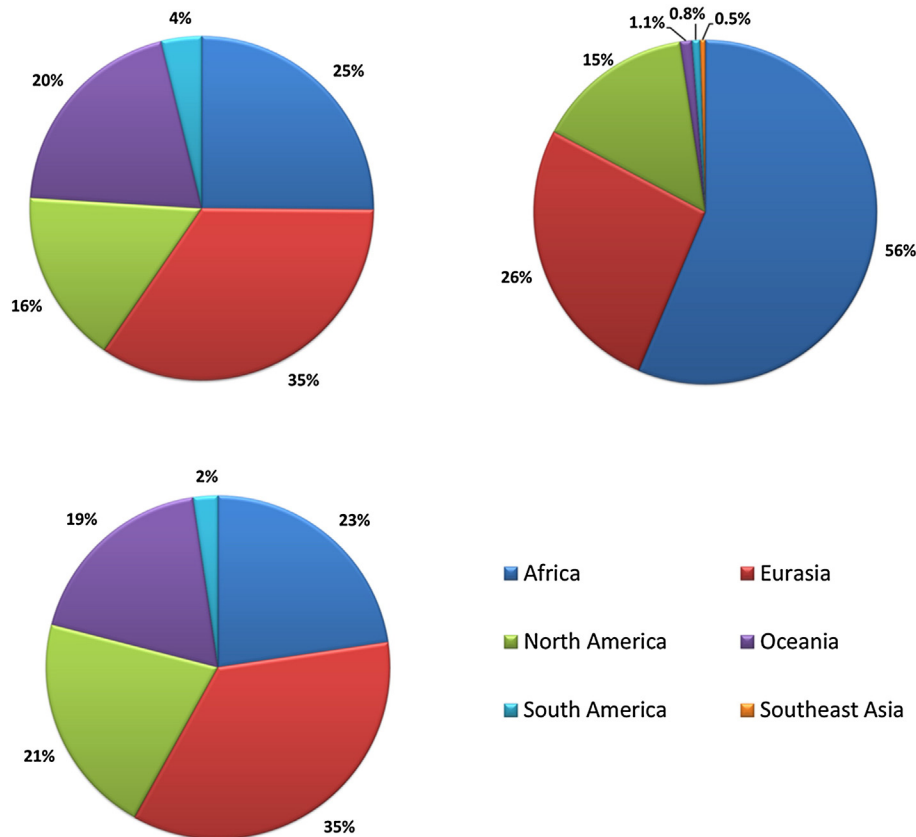


Fig. 10. Geographic split of global oxide MODUM resources inclusive of reserves. All charts show the percentage of total contained oxide ore (chromite) or metal oxide (for vanadium and ilmenite deposits) in reserves and resources for each region shown. Where a region is not shown, there are no resources or reserves reported. A. Data for chromite. B. Data for vanadium. C. Data for ilmenite. Data are based on the information provided in Appendix 2 and primarily sourced from SNL Metals and Mining (2014a).

Table 5

Global mine production from all deposit types for 2013.

	Ni	Cu	Au	Pt	Pd	Rh	Chromite	Ilmenite ^a	V ₂ O ₅
Production unit	tonne	tonne	Troy ounce	Troy ounce	Troy ounce	Troy ounce	tonne	tonne	tonne
Mine production	2,211,500	18,082,000	89,057,259	5,740,000	6,430,000	721,000	26,000,000	12,928,007	127,000
Production source	INSG	ICSG	LME	JM	JM	JM	USGS	USGS	USGS
Average price (\$US/unit)	15,007	7,322	1,411	1,490	727	1,067	700	200	14,550
Price source	LME	LME	Kitco	JM	JM	JM	USGS	USGS	Infomine
Value of production (\$US M)	33,188	132,404	125,680	8,554	4,674	769	18,200	2,586	1,848
% of global metal markets	3.3%	13.2%	12.6%	0.9%	0.5%	0.1%	1.8%	0.3%	0.2%

Abbreviations used:

INSG = International Nickel Study Group; ICSG = International Copper Study Group; JM = Johnson Matthey 'Platinum 2013' Report.

USGS = United States Geological Survey; LME = London Metal Exchange.

^a Tonne ilmenite estimated from TiO₂ grade and assuming stoichiometric ilmenite composition.

(Table 7). For reference, diamond exploration spend for 2013 (dominated by Africa and Eurasia) shows a similar lack of geographic diversity to that seen for PGE (dominated by Africa and North America; Fig. 14, Table 7). The strong correlation between market size and geographic diversity in exploration (and mining) projects is hard to dispute and is interpreted here to reflect a sustained focus on established mining camps and mineral districts in the case of smaller market commodities. The importance of market size as a driver of exploration strategy rivals the importance geological factors affecting the decision of where to explore. The historical bias toward brownfield exploration for smaller market commodities implies that much of the world remains significantly under-explored for PGE, chromite, vanadium and ilmenite.

Since early 2012, junior markets in the western world have experienced a large decline in investor interest and the availability of financing for both exploration and development projects. This has led to a pronounced increase in the proportional exploration spending made by major mining companies versus junior companies and to a bias toward lower risk mine site (brownfield) and advanced-stage projects versus greenfield projects. Nickel exploration spending in 2013 was dominated by major and intermediate companies (~\$400 million) with junior companies accounting for less than 25% (\$112 million) of total global exploration budgets (SNL Metals and Mining, 2014b). Similarly, 2013 exploration spending for PGE was dominated by advanced exploration, development and mine site projects (\$99 million) in comparison to grassroots projects (\$32 million) (SNL Metals and Mining, 2014b).

This trend reflects the current risk aversion in the commodity-based stock exchanges (TSX, ASX and NYSE) that contrasts with the fact that many metals including gold, palladium, copper and nickel are currently priced above their pre-2006 to 2008 commodity boom inflation-adjusted 20 year average prices (e.g., http://www.kitco.com/scripts/hist_charts/). With continued strong fundamentals in metal prices and global demand, sustained investment into exploration for new, high-quality nickel, PGE and chromite deposits is justified, particularly in the context of the size (annual production value) of their respective markets and their residual geological prospectivity. Prices should remain strong as long as industrial demand continues to grow, even if the pace of that growth is lower than it has been during the past 15 years when the Chinese economy surged, leading to unprecedented demand growth for most commodities. In terms of value, many MODUM deposits constitute 'Tier 1' assets, which are generally defined as large, expandable, long life (>20 years) mines with favorable mineralogy and geographic location and in the lower half of the cost curve. Tier 1 MODUM assets are capable of sustaining profitable mining over many economic cycles, with the best examples being the Noirl'sk-Talnakh operations in Russia, the Sudbury operations in Canada, and the Bushveld PGE and chromite mines in South Africa. In terms of residual exploration prospectivity, significant new and high value PGE, chromite, vanadium and nickel-copper sulfide deposits continue to be made in both greenfield and brownfield environments, with selected examples including the Waterberg PGE discovery in South Africa

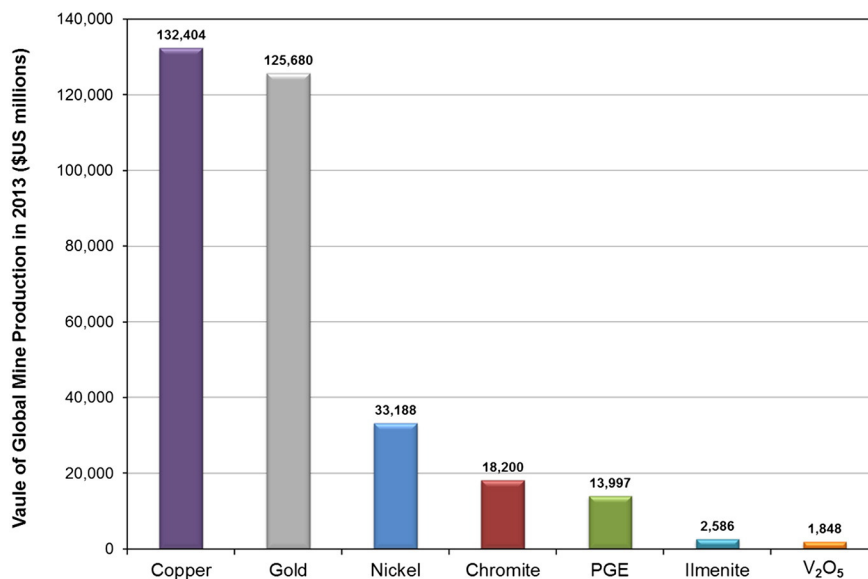


Fig. 11. Total value of estimated 2013 mine production for MODUM-related commodities including all deposit types. The numbers placed above the bars for each commodity represent the estimated value of mine production for that commodity. Data are derived from Table 5.

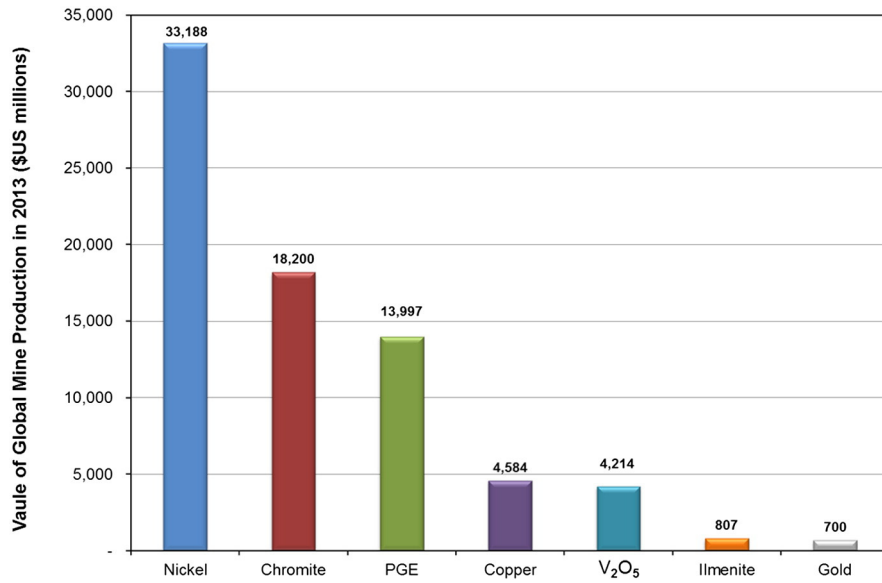


Fig. 12. Total value of estimated 2013 mine production for MODUM-related commodities based solely on production from MODUM. The numbers placed above the bars for each commodity represent the estimated value of mine production for that commodity. Data are derived from Table 5.

(www.platinumgroupmetals.net), the Nova nickel discovery in Western Australia (www.siriusresources.com), the Maracas vanadium deposit in Brazil (www.largoresources.com), and the "Ring of Fire" chromite discoveries in northwestern Ontario (<http://norontresources.com/>).

6. Discussion

An informed view of the essential attributes of the MODUM-related commodity markets is important for strategic planning for the metals

and industrial mineral exploration and mining sectors. This is especially true for strategic metals and minerals having geographically restricted supply such as vanadium and chromite, which are used in armament production and general infrastructure purposes; and, the PGE, which are an essential component of catalytic converters for both diesel- and gasoline-burning vehicles. The information presented above is primarily concerned with current global resource and production data and recent exploration spending trends for MODUM-related commodities in a regional context. The following discussion considers the supply, demand, processing and sale of MODUM-related commodities, providing the

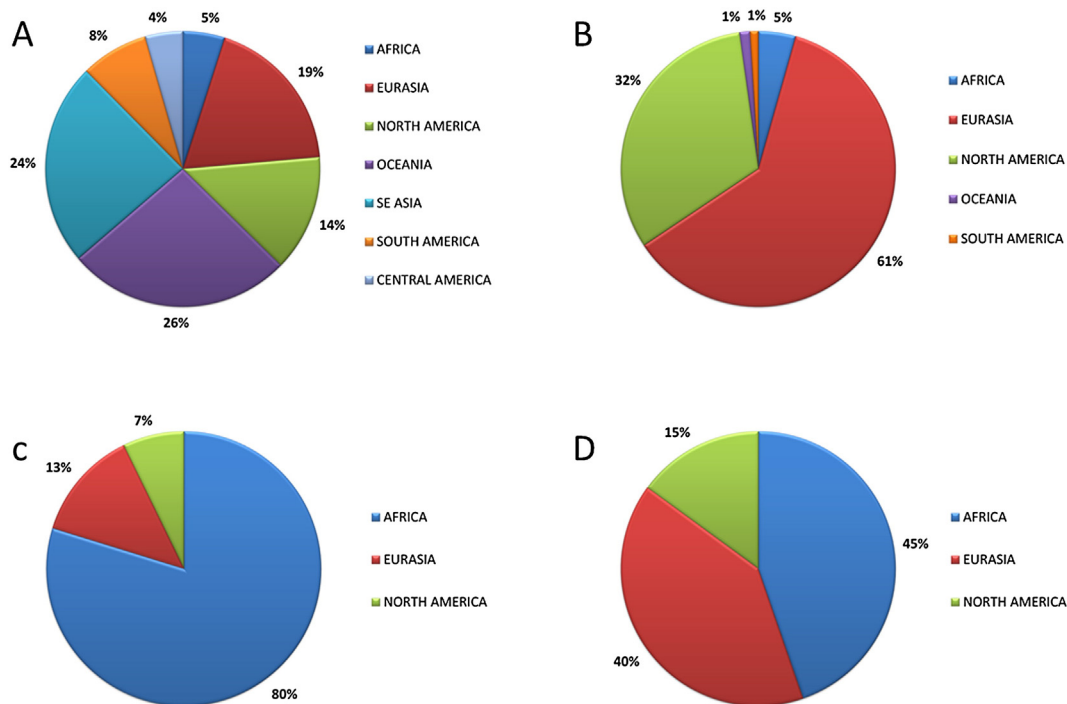


Fig. 13. Geographic split in actual 2012 global mine production from MODUM sulfide and nickel laterite projects by commodity. Numbers placed around the pie charts are the estimated percentage share of the total value of mine production for the specified commodity in each region shown. Data are derived from sources listed in Table 5 and from SNL Metals and Mining (2014a). Where a region is not shown, there are no resources or reserves reported. A. Nickel mine production for both sulfide and laterite projects. B. Copper mine production for sulfide projects. C. Platinum mine production for sulfide projects. D. Palladium mine production for sulfide projects.

Table 6Statistical summary of global exploration spending in 2013. Principal source: *SNL Metals and Mining* (2014b).

Country	Au exploration spend		Cu exploration spend		Ni exploration spend		PGE exploration spend		Diamond exploration spend		Total exploration spend ^b	
	(\$US M ^a)	(% of total)	(\$US M)	(% of total)	(\$US M)	(% of total)	(\$US M)	(% of total)	(\$US M)	(% of total)	(\$US M)	(% of total)
# countries	115	–	84	–	45	–	10	–	20	–	–	–
Total – global	6,646	–	3,465	–	597	–	120	–	489	–	11,322	–
Total – Africa	1,187	17.9%	559	16.1%	48	8.0%	78	64.8%	155	31.7%	2,029	17.9%
Total – Eurasia	878	13.2%	459	13.3%	139	23.2%	2	1.7%	271	55.3%	1,750	15.5%
Total – North America	2,024	30.5%	615	17.7%	103	17.3%	32	26.6%	54	11.0%	2,829	25.0%
Total – Central America	97	1.5%	45	1.28%	11	1.8%	0	0.0%	0	0.0%	152	1.3%
Total – Oceania	1,094	16.5%	452	13.0%	199	33.3%	4	3.0%	10	1.94%	1,759	15.5%
Total – SE Asia	268	4.0%	186	5.36%	52	8.7%	0	0.0%	0	0.0%	506	4.5%
Total – South America	1,097	16.5%	1,150	33.2%	46	7.6%	5	3.9%	<1	<0.1%	2,297	20.3%

^a \$US M = millions of US dollars.^b Total exploration spend for all commodities listed in the table.

strategic background for an analysis of the geological controls on the location and spatial coincidence of MODUM. Specific key mineral belts for MODUM are subsequently examined in order to develop a risk-adjusted and value-based exploration strategy.

6.1. Commodity markets

As discussed in Tilton (2006), Mudd et al. (2013) and Mudd and Jowitt (2014) there does not appear to be a significant risk of exhausting the known resources for most major commodities, including nickel and copper, for the next several decades. In the case of nickel, global resources including reserves were estimated by Mudd and Jowitt at ~300 million tonnes of nickel metal, an amount these authors project as representing >100 years of global mine production assuming a constant rate of 1.9 million tonnes per year. For copper, global reserves and resources are estimated at between 1.8 and 2.2 billion tonnes that, using a future growth rate in global copper mine production calculated from 1950 to 2010 output, represents at least 80 years of global mine supply (Mudd et al., 2013). A similar view is presented here for oxide-type MODUM and PGE resources as supported by the global resource data presented in Tables 1, 2, 5 and 7 and with reference to previous, similar compilations (e.g., Cawthorn et al., 2005; Mudd, 2010). Between 2005 and 2008 there was a major correction to long term metal prices for many base and precious metals that reflected a surge in global demand, primarily led by China, for almost all metals and industrial minerals. This price adjustment was probably also supported by the continued lowering of average global mining grades for most major metals and minerals in response to increased use of bulk mining methods and the related decline in the proportion of global mine supply that is sourced from the highest-grade deposits (Snow and Juuhas, 2002; Mudd et al., 2013).

Nickel remains an essential component of stainless steel and its supply-demand fundamentals are inextricably linked to global economic conditions and more specifically to the demand for stainless steel in both advanced and emerging economies. Global nickel production recently became dominated by laterite projects after prior decades in which sulfide projects were the largest source of global nickel mine supply (Mudd, 2010; Table 5). The exact year that this occurred is open to debate but is estimated to have occurred around 2009 or 2010. Looking

forward, it is expected that laterite projects will continue to increase their share of global nickel mine production over the next decade in the absence of major new high-value sulfide nickel discoveries and development projects. Since ~2000, the growth in global stainless steel production has almost exclusively been led by the expansion of the Chinese steel manufacturing sector; a clear reflection of the rapid growth of China's economy and its major, sustained investment into infrastructure. Despite growing demand global nickel markets have recently been in surplus (e.g., LME stock levels for nickel in March 2015 were averaging >400,000 tonnes of nickel metal; <http://www.lme.com/metals/non-ferrous/nickel>). This surplus reflects the continued ramp up of large scale laterite nickel mines such as Vale's Onca Puma mine in northern Brazil and First Quantum's Ravensthorpe mine in Western Australia. With large annual production volumes and continual improvements in processing efficiencies many integrated laterite mining and processing operations, including pyrometallurgical and hydrometallurgical plants, are increasingly competitive on a net of byproduct cost basis compared to historically advantaged nickel sulfide mines. Continued refinements to current laterite nickel processing technologies should lower the economic grade requirements for limonite, transitional silicate-oxide and saprolite deposits (Marsh and Anderson, 2011). Laterite pyrometallurgical facilities used to treat saprolitic nickel laterite deposits operate at higher temperatures and treat much larger volumes of ore than nickel (copper) sulfide smelters. This has led to the current situation in which profitable pyrometallurgical laterite mining operations are generally confined to jurisdictions having established, cheap electric power or the ability to construct near-site hydro-electric power generation plants (e.g., Brazil, southeast Asian countries and New Caledonia). The recent successes of some hydrometallurgical plants that are used to process transitional and limonitic laterite deposits is concurrently unlocking the value of the vast resources of these typically lower grade laterite deposits, particularly those in Australia, New Caledonia and Brazil. The recent phenomena of Chinese nickel pig iron production has caused significant growth in nickel demand from laterite deposits in southeast Asia, particularly in Indonesia. Despite the expected sensitivity to nickel price, the shipment of unprocessed laterite ore from Southeast Asian countries to China has continued more or less unabated for the past decade. It is not yet clear how significantly the recent ban on the shipment of unprocessed laterite ore by Indonesia will impact the nickel pig iron industry in China. In the absence of exports from Indonesian other Asia-Pacific nickel mining countries may step up to meet the needs of the Chinese nickel pig iron industry. The increased size and diversification of production in the global nickel market makes it less susceptible to major price crashes in the wake of global economic downturns. This provides an important motivation for longer-term investment into nickel-bearing MODUM. A similar logic applies to copper-rich MODUM given that the global copper market is much larger and has even greater geographical diversity in supply.

Table 7

Exploration spending and value of production.

Source: *SNL Metals and Mining* (2014a,b).

Commodity	2013 spend (\$US M)	2013 production value (\$US M)	2013 spend % of production	# countries
Gold	6,646	125,680	5.29%	115
Copper	3,465	132,404	2.62%	84
Nickel	597	33,188	1.80%	45
PGE	120	13,997	0.86%	10
Diamonds	489	14,800	3.31%	20

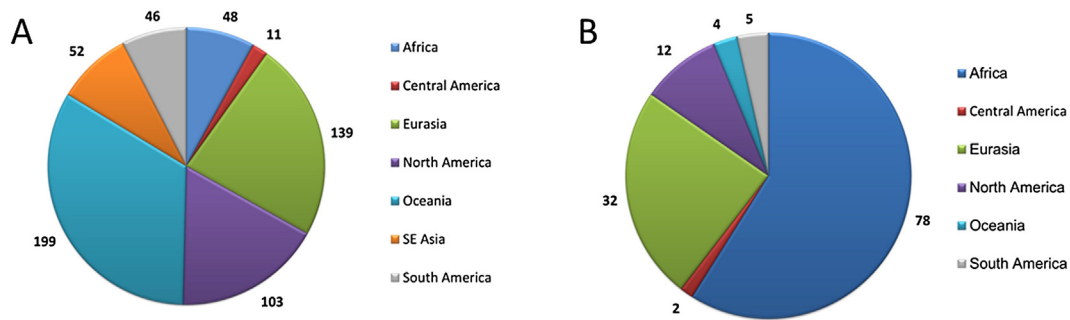


Fig. 14. Geographic split in exploration spending for MODUM-related Ni (Cu) and PGE projects in 2013. Numbers placed around the pie charts are the estimated total annual exploration spend in millions of US dollars for the specified commodity for each region shown. Data are derived from Table 6 and are principally sourced from SNL Metals and Mining (2014b). Where a region is not shown, there are no exploration spending data reported. A. Spending split for Ni(Cu) sulfide projects. B. Spending split for PGE projects.

The current global PGE market is dominated by South African mine supply but features a globally diversified demand. The total value of global PGE consumption in 2013, including mine production and an increasingly significant amount of secondary supply drawn from the recycling of catalytic converters is estimated at \$20.5 billion (Johnson Matthey, 2013). PGE demand is inextricably linked to global vehicle sales and to increasingly stringent emission control regulations especially for large developing economies such as the Chinese economy (Johnson Matthey, 2013). Global platinum markets are currently in surplus despite supply disruptions in 2014 caused by the South African platinum miners' strike action. This surplus can largely be attributed to a prolonged period of substitution of palladium for platinum in auto-catalysts used in gasoline-burning vehicles. The persistence of a weak Rand compared to the US dollar is likely to further exacerbate the surplus in platinum markets by spurring increased mine production from Bushveld Complex platinum producers or, at the least, propping up otherwise uneconomic platinum mines. In contrast, palladium markets have developed a large supply deficit that was estimated at ~700,000 oz or >10% of palladium mine supply in 2013 (Johnson Matthey, 2013) and was forecast to grow to 1.6 million oz in 2014 (<http://www.platinum.matthey.com/services/market-research/may-2014>). Despite positive market fundamentals for palladium, there appears to be little to no immediate relief on the supply side forthcoming

from either new mining projects or expansions to existing operations. This bodes well for current palladium producers. However, a unique and ongoing risk factor for palladium producers is the amount of palladium metal being sold into the global market by Russia. Russian palladium supply historically included large but relatively stable palladium production from Noril'sk Nickel's Taimyr nickel–copper sulfide mining operations and highly variable quantities of palladium sold from unquantified Russian government stockpiles. Recent proclamations by many PGE market analysts of a seriously diminished or exhausted Russian government palladium stockpile appear suspect in light of an announcement by Noril'sk Nickel that it was considering the purchase of palladium from the Russian government in order to meet the needs of its customers (<http://www.bloomberg.com/news/articles/2010-05-19/>). A reality of PGE markets is the significant historical price volatility, with each of the key industrial PGE (platinum, palladium and rhodium) showing erratic price changes over the past two decades (<http://www.kitco.com/charts/>). An additional and more recent risk to global PGE markets is the behavior of commodity-based exchange-traded funds (ETFs) that can hold substantial physical quantities of both metals (Johnson Matthey, 2013). Platinum and palladium ETFs provide investors with direct exposure to PGE price fluctuations through the holding of physical metal that is bought and sold by the fund. In 2014, physical platinum and palladium held in ETFs exceeded three million ounces

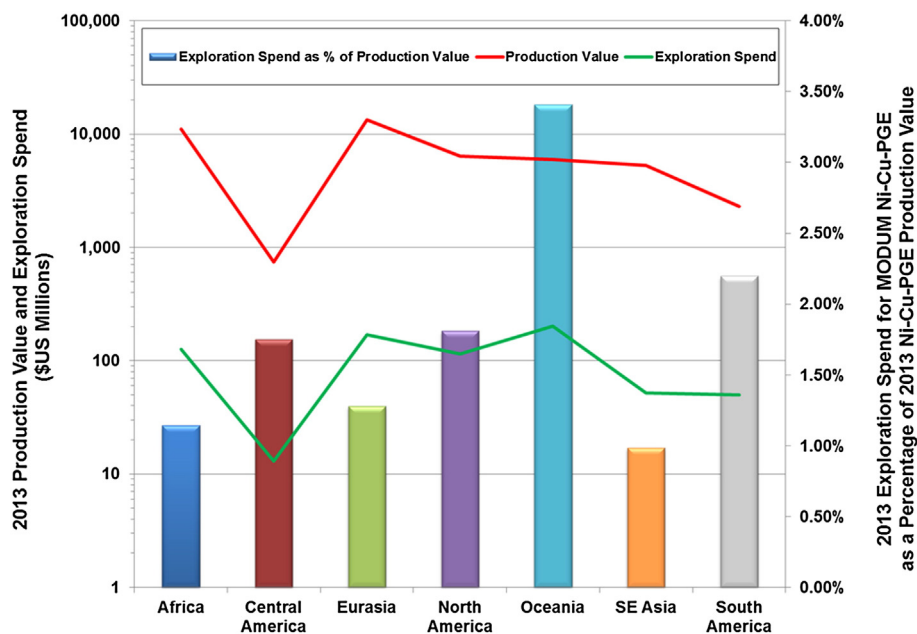


Fig. 15. Geographic split in 2013 global nickel (± copper) exploration spending as a percentage of global nickel mine production. Histogram bars represent exploration spend as a percentage of 2013 mine production value. Data are principally sourced from SNL Metals and Mining (2014b).

for both metals. Although an unwanted, additional uncertainty for producers, speculative buying and selling by ETFs is now a major factor in determining platinum and palladium prices.

As discussed above, chromite represents a large and growing industrial minerals market. However, details of global chromite markets remain poorly understood because of the lack of transparency in refining costs, feed grades (purity) and sales contracts. Like nickel, chromite consumption is linked to the global demand for steel. In contrast to nickel, which is largely traded through the London Metals Exchange, chromite is typically mined and distributed 'off market' within integrated steel manufacturing operations or through direct purchase contracts between steel plants and chromite producers. Accordingly much of the world's chromite production is buffered from the laws of supply and demand that freely-traded commodities adhere to. Despite historically limited investment into chromite exploration worldwide, new deposits continue to be found, sometimes accidentally as was the case for the original chromite discoveries in the "Ring of Fire" district in northwestern Ontario that were first detected in nickel sulfide exploration programs (Laarman, 2014). It is important that chromite explorers directly investigate the specific metallurgical requirements of steel manufacturers operating in their region(s) of focus. This will facilitate the definition of threshold values for chromite composition, deleterious gangue minerals and minimum tonnage for new discoveries and allow investment to flow to projects capable of outperforming current suppliers to these steel manufacturers. Even if chromite is not the primary target for a given MODUM exploration program, knowing what constitutes an economically attractive grade-thickness chromite intersection allows the exploration company to react quickly in the event that a nickel- or PGE-focused program encounters significant chromite concentrations.

Vanadium markets have also been growing in recent years in response to increased demand for vanadium-rich steel that is primarily used in high-strength applications such as high-speed tools and vehicle gears and crankshafts. There are also a number of potentially significant future applications for vanadium including high density vanadium batteries. Although a significant amount of current vanadium supply is produced from oxide MODUM other important sources exist. These include secondary production from oil refining (fly ash residue) and primary or byproduct vanadium derived from polymetallic black shale deposits (e.g., Gibellini deposit, Nevada, USA; Hanson et al., 2011). Vanadium is typically sold as ferrovanadium in the form of vanadium-rich slag that can be directly used in the manufacture of vanadium-bearing steel. It is also sold as vanadium pentoxide for use in the manufacture of sulfuric acid. Processing methods commonly employed for vanadium ores are generally part of integrated steel plants that employ vanadium-bearing magnetite $\pm$ ilmenite $\pm$ titanium-bearing magnetite concentrates from nearby stratiform magmatic oxide deposits. With current vanadium prices, vanadium-rich deposits and mineral concentrates produced at the mine site have sufficient value to export to overseas steel manufacturing facilities, opening up many new jurisdictions for primary vanadium exploration and development. Typical bedrock resource grades range from ~0.1% to ~1% V_2O_5 whereas grades in the primary ore mineral, vanadium-bearing magnetite, can reach 2% and higher (Arsenault et al., 2013; Cawthorn et al., 2005).

Titanium dioxide remains an important industrial commodity that is largely sourced from rutile and lesser ilmenite and leucosene in heavy mineral sand deposits in coastal regions of the eastern USA, southern Africa, India and Australia (Force, 1991). Primary industrial demand is dominated by the pigment industry where TiO_2 , generally in the form of synthetic rutile, is used as a whitening agent. Very few primary ilmenite deposits have ever been developed but with sufficient grade and tonnage some of these have proven to be profitable (e.g., Rio Tinto's Lac Tio deposit, Quebec, Canada; Charlier et al., 2010). As the quality and availability of large tonnage but lower grade heavy mineral sand deposits dwindles, bedrock ilmenite deposits having purity and appropriate textures (i.e., coarse-grained and easily liberated ilmenite as

opposed to lamellar ilmenite in magnetite) should become more attractive for development. Primary ilmenite mines typically employ a chlorination or sulphuric acid leach process to extract the titanium from ilmenite concentrates generated at the mine using gravitational and/or magnetic separation methods. In deposits in which ilmenite is intergrown with vanadium-bearing magnetite, the contained titanium reports to a titanium slag during the smelting process. High-grade primary ilmenite resources are known from several countries and regions of the world, with numerous examples occurring in North America, Australia, Scandinavia and China (Table 2). Recently defined resources include high-grade ilmenite deposits associated with late oxide-ultramafic intrusions into the western margin of the Duluth Complex (Severson, 1995; Johnson et al., 2012). Although known for many years, these deposits have been shown to contain economically attractive grades and thicknesses and, being hosted by iron-rich ultramafic rocks, occur in a non-traditional setting that opens up new exploration possibilities. Unfortunately, ilmenite remains a low value bulk commodity (~\$200/tonne for US imports in 2013, Table 5) and that makes direct shipping of raw concentrate to distant markets very unattractive. For future explorers, a reality of ilmenite markets is the need to define suitably large and high-grade primary resources that can support the major capital investments required to develop on-site processing and refining to synthetic rutile or to titanium metal – the latter of which is increasingly used in the aerospace industry. Alternatively, the many known undeveloped resources containing intergrown vanadium-bearing magnetite and ilmenite could in future, with appropriate tonnages and grades, support investment into established pyrometallurgical processing plants where pig iron, titanium-slag and vanadium-rich slag can all be produced at site. In these situations, metamorphic grades can play an important factor in upgrading the value of iron–titanium–vanadium oxide deposits. As an example, the undeveloped vanadium-bearing magnetite–ilmenite deposit at Pipestone Lake, Manitoba, Canada is believed to have been upgraded by regional amphibolite facies metamorphism from an initially complex intergrowth of titaniferous and vanadium-bearing magnetite to free milling, coarser-grained ilmenite and vanadium-bearing magnetite (Jobin-Bevans, 1997).

A difficult aspect of developing a practical and sustainable exploration strategy, particularly for non-producing companies, is the adoption of minimum targets for grade, thickness and resource size. Although it is not advised to develop overly-explicit guidelines for exploration projects, it is deemed critical that exploration companies have a good appreciation of current and forecast future economic thresholds for the commodities being sought. As an example, a review of current nickel mining operations in terms of the NSR value of the combined resource and reserve and the milling rate and production value of the operation (Figs. 16 and 17) provides economic guidelines for nickel explorers. Fig. 16 plots tonnage milled against the NSR value of the global resource and reserve for 76 mining operations based on estimated production figures for 2013 (SNL Metals and Mining, 2014a). Operations are divided into very small, small, medium-large and very large based on the tonnes of ore milled (2013 data). A further economic classification involves marginal, attractive and premier projects (Fig. 16). The proposed field for premier deposits is dominated by underground sulfide mines collectively showing a wide range in production (milling) rates. The highest NSR values are almost exclusively associated with nickel sulfide mines (Fig. 16). Open pit sulfide deposits appear to require resources with a minimum NSR value of ~\$40/tonne to become attractive mining operations. At current prices (Table 3) this minimum NSR value equates to minimum nickel equivalent grades of ~0.4%, copper equivalent grades of ~0.8% and platinum equivalent grades of 1.5 g/t. Laterite projects and underground sulfide deposits both appear to require a minimum ore value of ~\$70/tonne to become attractive mining operations. At current prices this minimum NSR value equates to minimum nickel equivalent grades of ~0.7%, copper equivalent grades of ~1.4% and platinum equivalent grades of ~2.5 g/t. Underground sulfide

deposits can clearly operate at small scales (e.g., less than one million tonnes milled per year) and still deliver attractive economics based on high mill feed NSR values extending to >\$500/tonne (Fig. 16) and equating to a ~5% nickel equivalent grade. Several large-scale underground nickel sulfide operations have grades similar to the majority of the nickel laterite and open pit nickel sulfide operations shown. The largest of these are integrated mining and processing facilities tapping multiple deposits in a single mining district, including the Sudbury and Noril'sk–Talnakh mining camps (Naldrett, 2004). Clustering of high-value magmatic sulfide deposits along a specific structure or in a single magmatic province remains a major inducement for nickel exploration companies.

Fig. 17 plots the gross production value of all metals (2013 data) for the same 76 operations against the average NSR value per tonne of the combined resource and reserve. In this plot, the operations are classified by sub-type with sulfide projects split out into nickel-rich, nickel-copper, nickel-copper-PGE and PGE-rich operations and laterite projects are subdivided into limonite (oxide) + clay and saprolite subtypes. The plot identifies a small number of very high-revenue premier nickel mining operations and of these, most are sulfide projects with significant copper and/or PGE content. In terms of net smelter return value, the highest value mineral resources (>\$200/tonne) are associated with sulfide projects with one exception (a saprolite mine). This is one of the appeals of sulfide projects in comparison to laterite projects. Nickel sulfide mining operations can be extremely large and/or extremely high grade, can support surface or underground mining, and feature highly variable production rates. In contrast, laterite mining projects collectively represent a much more restricted range in the average NSR value and grade of the supporting resource and reserve, despite having attractive resource sizes (commonly >100 million tonnes; Fig. 17). The least attractive projects include several small sulfide and saprolite mines and a few small limonite operations; all having relatively low NSR value resources (Fig. 17). Attractive deposits are considered to be those with >\$50 million of production value. The average NSR value of the combined resources and reserves for these attractive projects covers a large range from ~\$60/tonne to ~\$520/tonne.

6.2. Key mineral belts

The moniker 'key mineral belt' as discussed below is intended to describe a geologically distinctive and geographically restricted terrane that contains multiple resources of a given category of ore deposit. A commonly cited example of a key mineral belt is the Andean copper province (Sillitoe and Perello, 2005), one of the richest mineral provinces ever discovered. In the case of MODUM, a key mineral belt is herein defined as hosting at least 1% of the earth's currently known metal or mineral endowment (= current resource and reserves plus previously mined reserves and resources) for at least one of the MODUM commodities, in one or more spatially related magmatic events, and featuring one or more of the deposit types described in this paper.

Table 8 provides an estimate of total nickel endowment for the 30 top-ranked key mineral belts based on data for both laterite and sulfide deposits. Historical production figures in Table 8 were estimated from a large number of published sources including the United States Geological Survey annual mineral commodities summaries, data from state and provincial government bureaus of mines, mining company annual reports and SNL Metals and Mining (2014a). The data presented in Table 8 compare favorably with those of Mudd (2010 and 2012) and Mudd and Jowitt (2014). Table 8 also provides estimates of the number of current (2013) operations in the individual key mineral belts listed as well as general information on recent, significant discoveries in those belts.

In terms of the in-ground value of the total nickel endowment, the world's nickel resources are roughly evenly split between laterite provinces and sulfide districts (Table 8). On a geographic basis, the world's historical total nickel endowment is dominated by several key mineral belts (Fig. 18a) with laterite provinces in Southeast Asia having

nearly double the amount of contained nickel than any other belt (Table 8). Amongst the sulfide provinces listed, the Sudbury Igneous Complex and the Siberian flood basalt province (host to Noril'sk–Talnakh) have the highest total nickel endowment (Table 8). Sulfide provinces and laterite provinces show little geographical overlap. This reflects the limited extent of ancient cratonic nuclei, which preserve large mafic to ultramafic magmatic provinces and their attendant sulfide deposits, in the lower latitudes of both the northern and southern hemisphere. These equatorial regions host abundant Phanerozoic ophiolite complexes that, under specific tropical weathering conditions, can develop into large nickel laterite deposits. Notable exceptions to this geographic split between sulfide and laterite deposits include:

- the Yilgarn Province in Western Australia that contains numerous 'dry laterite' deposits (Golightly, 2010; Marsh and Anderson, 2011) and proximal nickel sulfide resources (Barnes, 2006); and,
- the Precambrian cratons in Brazil and south-central part of Africa (Table 8).

Although known since the 1800s, large deposits of nickel-copper-cobalt-manganese nodules on the seafloor have recently gained more attention as a potentially important future source of these metals. Tonga Offshore mining Ltd. produced an initial resource estimate of 440 Mt of inferred resources grading 1.2% nickel, 1.1% copper, 0.24% cobalt and 26.9% Mn (Nimmo, 2013). Despite the significant depths of most seafloor nodule deposits and associated, significant technical obstacles to their development, their high grade and large contained metal value will likely to continue to motivate exploration investment.

On a total contained metal value basis, southern Africa, central-eastern North America and Western Australia dominate the known resources associated with nickel-copper-PGE sulfide deposits (Fig. 18). Looking at the discovery track record, most of these resources were found and developed in the early to mid-1900s (Naldrett, 2004) with relatively few high value deposits having been discovered in more recent decades (Table 8); Voisey's Bay being one significant exception (Naldrett et al., 1996b; Naldrett and Li, 2007). The recent deficit in major new discoveries of nickel sulfide deposits should be understood in terms of both the residual prospectivity of a specific key mineral belt and the intensity and depth of exploration in greenfield environments. Nickel sulfide exploration was, up until recently, led by major mining companies holding large land packages adjacent to their operations and with a predilection toward incremental brownfield exploration to maintain a resource and reserve base. Despite these advantages very few nickel mining companies have been able to deliver multiple high value nickel sulfide discoveries within their strategic mineral tenements. This is believed to be (in part) a reflection of the tendency of large deposits to be found early in the history of a key mineral belt because of their larger exploration footprint. There is also an inverse correlation between the depth of exploration and/or intensity of drilling and distance from significant ore deposits that tends to fall off rapidly (e.g., to depths of <500 m) within a few km from an existing mine property. During the first decade of the twenty-first century an explosion in greenfields exploration investment occurred that was led by the junior sector, following on the heels of a period of consolidation in the 1990s featuring the acquisition of three major nickel-focused mining companies (Inco, Falconbridge and Western Mining) by global diversified miners. In the 2000s, junior nickel explorers faced limited competition from major nickel miners and led a push into west and east-central Africa, the Canadian Arctic, the coastal parts of Greenland, the Russian far north and far east, the western and northern parts of China, the interior of the Australian continent and the more remote parts of northern and western Brazil. Despite high indicated nickel prospectivity in these areas, very few major discoveries were made. Some notable exceptions include Mirabela Nickel's Santa Rita nickel-copper sulfide deposit in Bahia State, Brazil (Barnes et al., 2011) and Sirius Resources' Nova and Bollinger nickel-copper-cobalt deposits in the Fraser Range of Western Australia (<http://www.siriusresources.com.au/>). The lack of significant, recent

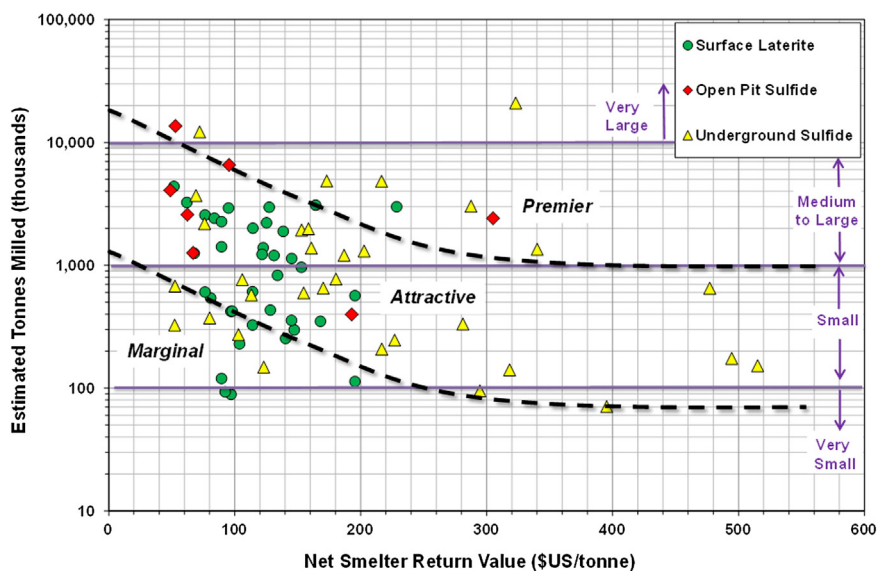


Fig. 16. Estimated annual ore tonnes milled for sulfide and laterite mining operations versus net smelter return value of resources and reserves with suggested economic classifications for marginal, attractive and premier operations and very small, small, medium-large and very large mining operations. Data are principally sourced from SNL Metals and Mining (2014a).

greenfields nickel sulfide discoveries is partly ascribed to the high cost of exploring in remote frontier belts that commonly feature extremely short field seasons. However, the major cause of the dearth of recent discoveries is believed to be the traditional boom and bust cycle of the junior exploration investment sector (Connolly and Orsmond, 2011). Cessation of investor interest during market downturns reduces the probability of success by limiting the duration of effective exploration programs, especially in higher-risk greenfields and frontier belts where perseverance is an essential ingredient of success. Historically, major producers were responsible for the majority of global greenfields nickel sulfide exploration spending and were able to sustain efforts in specific frontier belts over multiple cycles. This is no longer the case.

For the PGE, the small amount of annual exploration expenditures (Table 6) and the relatively small size of the global PGE market (Fig. 11) remain deterrents to new discoveries. On a contained value basis, the PGE resources hosted by the Bushveld Complex and the Great Dyke in

southern Africa continue to attract the majority of exploration investment both for advanced projects and grassroots projects (Table 6, Fig. 14). Elsewhere, the lack of investment in PGE exploration assures that significant new discoveries are unlikely to occur despite the highly prospective nature of many mafic to ultramafic magmatic belts and the increased understanding of geological processes leading to economic PGE (and Ni, Cu) concentrations in magmatic sulfide deposits (Arndt et al., 2005).

The concept of key mineral belts has not, to the author's knowledge, been specifically applied to oxide MODUM although there are now sufficient data to do so. For chromite, there are multiple deposits recognized in several different geological provinces including podiform chromitites associated with ophiolite complexes in several different continental margin arc terranes (e.g., eastern Mediterranean region and Philippines; Fig. 18) and stratiform chromite deposits in large layered ultramafic to mafic complexes (e.g., southern Africa region – Bushveld Complex and Great Dyke; Fig. 18). Vanadium-bearing magnetite deposits

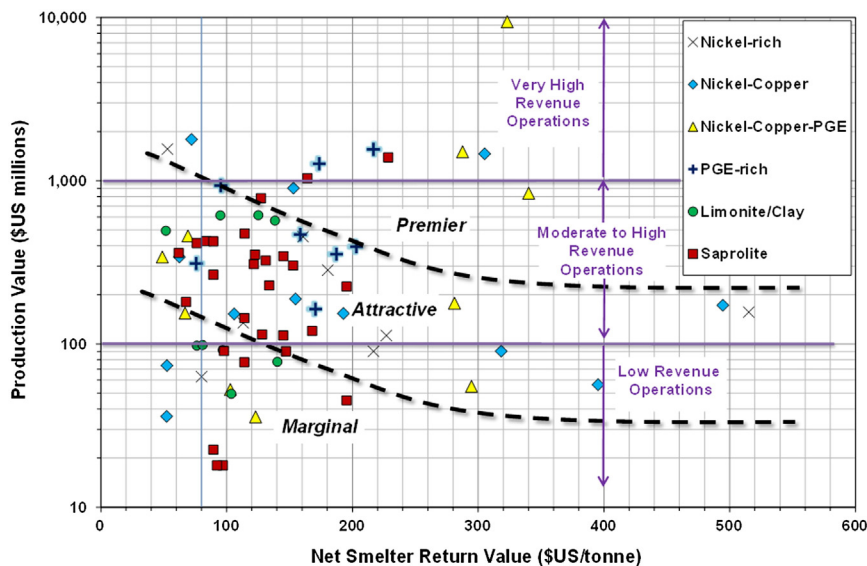


Fig. 17. Annual production value of all metals versus estimated net smelter return value of resources and reserves for sulfide and laterite mining operations with suggested economic classifications for marginal, attractive and world-class operations and low, moderate-high and very high revenue mining operations. Data are principally sourced from SNL Metals and Mining (2014a).

Table 8

Nickel endowment ranking.

Belt/province/suite	Region	Country	Belt classification	Age	No. of operations (2012)		
SE Asia ophiolites	SE Asia	Indonesia, Philippines, PNG	Emerging	Jurassic to Tertiary	23		
Yilgran Province laterites	Oceania	Australia	Mature	Neoproterozoic	2		
Siberian flood basalt province	Eurasia	Russia	Emerging	Permian	2		
Caribbean plate ophiolites	Central America	Colombia, Cuba, Dominican Republic, Guatemala, Venezuela	Emerging	Cretaceous and Jurassic	3		
Sudbury igneous complex	North America	Canada	Mature	Paleoproterozoic	4		
New Caledonian ophiolites	Oceania	New Caledonia	Emerging	Jurassic to Tertiary	5		
Bushveld igneous complex	Africa	South Africa	Mature	Paleoproterozoic	22		
Eastern goldfields superterrane - sulfides	Oceania	Australia	Mature	Neoproterozoic	5		
Pechenga greenstone belt	Eurasia	Russia	Mature	Paleoproterozoic	1		
Gansu Province	Eurasia	China	Mature	Mesoproterozoic	1		
Carajas greenstone belt laterites	South America	Brazil	Emerging	Neoproterozoic or Paleoproterozoic	1		
Mediterranean ophiolite belt	Europe	Greece, Macedonia, Serbia, Albania, Turkey	Mature	Cretaceous and Jurassic	3		
Eastern Australian laterites	Oceania	Australia	Mature	Paleozoic	0		
Mid-continent rift	North America	Canada, US	Emerging	Mesoproterozoic	1		
Goias complex and magmatic arc laterites	South America	Brazil	Emerging	Neoproterozoic	3		
South-central Finland shield	Eurasia	Finland, Sweden	Mature	Mesoproterozoic	1		
Superior boundary zone (MB)	North America	Canada	Mature	Paleoproterozoic	1		
Wrangellia terrane (Kluane belt)	North America	Canada, US	Frontier	Triassic	0		
Abitibi greenstone belt	North America	Canada	Mature	Neoproterozoic	1		
Nain plutonic suite	North America	Canada	Emerging	Mesoproterozoic	1		
Tocantins belt laterites	South America	Brazil	Frontier	Neoproterozoic?	0		
Lapland greenstone belt	Eurasia	Finland	Frontier	Paleoproterozoic	1		
Superior boundary zone (QC)	North America	Canada	Emerging	Paleoproterozoic	1		
Kibaran and Ubendian belts	Africa	Tanzania, Burundi, DRC	Emerging	Mesoproterozoic	0		
Bahia belt - sulfides	South America	Brazil	Emerging	Archean and Paleoproterozoic	1		
Musgraves Province	Oceania	Australia	Frontier	Mesoproterozoic	0		
Selebi Pikwe greenstone belt	Africa	Botswana	Mature	Neoproterozoic	0		
Tati greenstone belt	Africa	Botswana	Mature	Neoproterozoic	1		
Guapore belt laterites	South America	Brazil	Frontier	Mesoproterozoic	0		
Youanmi superterrane	Oceania	Australia	Emerging	Neoproterozoic	1		
Panxi rift (Emeishan Province)	Asia Pacific	Vietnam, China	Emerging	Phanerozoic to Paleoproterozoic	1		
Lynn Lake greenstone belt	North America	Canada	Mature	Paleoproterozoic	0		
Jilin belt	Eurasia	China	Mature	Triassic	1		
Zimbabwe Craton	Africa	Zimbabwe	Mature	Neoproterozoic	4		
West Pilbara Craton	Oceania	Australia	Emerging	Neoproterozoic	0		
Bird River greenstone belt	North America	Canada	Mature	Neoproterozoic	0		
Ossa Morena belt	Eurasia	Spain, Portugal	Emerging	Paleoproterozoic	1		
East Kimberly terrane	Oceania	Australia	Emerging	Paleoproterozoic	1		
McFaulds greenstone belt	North America	Canada	Frontier	Neoproterozoic	0		
Goias District sulfides	South America	Brazil	Emerging	Neoproterozoic	0		
Shebandowan greenstone belt	North America	Canada	Emerging	Neoproterozoic	0		
Flin Flon - Snow Lake domain	North America	Canada	Mature	Paleoproterozoic	0		
Belt/province/suite	2012 Ni production (t)	Pre-2012 Ni production (t)	Resources & reserves contained Ni (t)	Total Ni endowment (t)	Value of contained Ni (\$US millions)	Recent discovery or development	Decade
SE Asia ophiolites	527,169	3,400,000	44,100,000	48,027,169	720,740	Ramu	2000s
Yilgran Province laterites	44,558	290,000	25,000,000	25,334,558	380,194	Numerous	1990s
Siberian flood basalt province	207,000	7,500,000	17,500,000	25,207,000	378,280	Maslovskoye	1990s
Caribbean plate ophiolites	91,908	3,400,000	21,000,000	24,491,908	367,548	Tres Juanes Sur	2000s
Sudbury igneous complex	99,157	18,700,000	3,151,000	21,950,157	329,404	Nickel Rim	1990s
New Caledonian ophiolites	185,460	4,500,000	15,000,000	19,685,460	295,418	Goro, Koniombo	2000s
Bushveld igneous complex	79,189	500,000	12,400,000	12,979,189	194,778	Waterberg	2010s
Eastern goldfields superterrane - sulfides	136,412	2,265,000	8,280,000	10,681,412	160,295	Nova Bollinger	2010s
Pechenga greenstone belt	53,000	2,400,000	4,700,000	7,153,000	107,345	Yuzhny Mine	2010s
Gansu Province	60,000	1,370,000	5,500,000	6,930,000	103,998	Jiuquan City	2000s
Carajas greenstone belt laterites	6,000	0	6,800,000	6,806,000	102,137	Jacare	1990s
Mediterranean ophiolite belt	44,799	400,000	5,220,000	5,664,799	85,011	Devolli	2000s
Eastern Australian laterites	0	400,000	4,400,000	4,800,000	72,033	SCONI	2000s
Mid-continent rift	3,000	0	4,500,000	4,503,000	67,576	Thunder Bay North	2000s
Goias complex and magmatic arc laterites	66,200	720,000	3,500,000	4,286,200	64,323	Santa Fe/Ipore	2000s
South-central Finland shield	45,518	222,000	3,528,000	3,795,518	56,959	Ruossakero	1980s
Superior boundary zone (MB)	24,200	2,160,000	1,452,000	3,636,200	54,568	William Lake	1990s
Wrangellia terrane (Kluane belt)	0	6,000	2,865,000	2,871,000	43,085	Wellgreen Extension	2000s
Abitibi greenstone belt	600	85,000	2,408,000	2,493,600	37,421	Montcalm	1970s

(continued on next page)

Table 8 (continued)

Belt/province/suite	2012 Ni production (t)	Pre-2012 Ni production (t)	Resources & reserves contained Ni (t)	Total Ni endowment (t)	Value of contained Ni (\$US millions)	Recent discovery or development	Decade
Nain plutonic suite	61,900	138,000	2,256,000	2,455,900	36,856	Reid Brook Zone	1990s
Tocantins belt laterites	0	0	1,470,000	1,470,000	22,060	Araguaia	2000s
Lapland greenstone belt	3,875	0	1,460,000	1,463,875	21,968	Sakati	2000s
Superior boundary zone (QC)	28,613	258,000	1,131,000	1,417,613	21,274	Nunavik Nickel	1990s
Kibaran and Ubendian belts	0	0	1,300,000	1,300,000	19,509	Dutwa	2000s
Bahia belt - sulfides	0	0	1,296,000	1,296,000	19,449	Santa Rita	2000s
Musgraves Province	0	0	1,260,000	1,260,000	18,909	Nebo-Babel	1990s
Selebi Pikwe greenstone belt	0	600,000	400,000	1,000,000	15,007	Dikoloti	2000s
Tati greenstone belt	12,215	120,000	749,000	881,215	13,224	Tekwane	2000s
Guapore belt laterites	0	0	827,000	827,000	12,411	Morro Sem Bone	1990s
Youanmi superterrane	29,334	54,000	539,000	622,334	9,339	Spotted Quoll	2000s
Panxi rift (Emeishan Province)	15,000	30,000	300,000	345,000	5,177	Gaujacun	1990s?
Lynn Lake greenstone belt	0	220,000	122,000	342,000	5,132	Lynn Lake	1950s
Jilin belt	10,000	300,000	0	310,000	4,652	Hongqiling	1960s
Zimbabwe Craton	9,348	120,000	69,000	198,348	2,977	Hunter's Road	1990s
West Pilbara Craton	0	27,000	142,000	169,000	2,536	Radio Hill	1980s
Bird River greenstone belt	0	17,000	97,000	114,000	1,711	Mayville	2000s
Ossa Morena belt	2,398	25,000	77,000	104,398	1,567	Agaublanca	1980s
East Kimberly terrane	7,360	29,000	57,500	93,860	1,409	Savannah	2000s
McFaulds greenstone belt	0	0	62,000	62,000	930	Double Eagle	2000s
Goiás District sulfides	0	50,000	10,000	60,000	900	Americano do Brazil	2000s
Shebandowan greenstone belt	0	200,000	27,000	227,000	3,407	Shebandowan	1970s
Flin Flon - Snow Lake domain	0	13,400	0	13,400	201	Nome Lake	1980s
Totals	1,854,213	50,519,400	204,955,500	257,329,113	3,861,719		
Average	44,148	1,202,843	4,879,893	6,126,884	91,946		

are developed in many tholeiitic mafic intrusive provinces but are best known in the evolved, iron-rich and stratigraphically uppermost portions of large layered mafic to ultramafic complexes (e.g., Mafic Series, Bushveld Complex; Cawthorn et al., 2005). The delayed onset of oxide mineral saturation in tholeiitic magmas as opposed to calc-alkaline and alkaline magmas makes tholeiites the preferred magma type for vanadium-bearing magnetite exploration. The highest value deposits occur in Archean and Proterozoic tholeiitic magmatic provinces in southern Africa, southern China, eastern Canada, eastern Brazil, northern Finland, the Kola region of northwestern Russia, Kazakhstan and western Australia (Fig. 18). For bedrock ilmenite, key mineral belts with high value resources are concentrated in Proterozoic gneissic terranes with abundant anorthosite massifs (e.g., Grenville Province, North America; Caledonides region, southern Norway; Fig. 18) and in mafic to ultramafic magmatic provinces in which ferrogabbroic differentiates are volumetrically significant (e.g., Pilbara and Yilgarn cratons, Australia; Kaapvaal and Zimbabwe cratons, southern Africa; Emeishan Province, southern China; Fennoscandian Shield, Finland and Russia; Fig. 18).

6.3. Exploration strategies

Very specific exploration strategies have been developed for the MODUM discussed in this paper. For magmatic nickel sulfides, prospecting and mapping, potential field surveys such as magnetics and gravity (Balch et al., 1998; Lightfoot, 2007), time domain electromagnetic surveys (e.g., Watts, 1997; Wolfgram and Golden, 2001; King, 2007), diamond drilling, borehole geophysical surveys (King, 2007) and lithogeochemical vectoring (Lightfoot, 2007) are proven exploration tools. For nickel laterites, topographic surveying, water table mapping, weathering intensity mapping, geochemical sampling, electrical and magnetic surveying, and reverse circulation drilling are established methods for defining resources (e.g., Butt, 2004; Elias, 2002; Golightly, 2010). For PGE-rich deposits, most of the major discoveries were made by following up on alluvial concentrations of dense platinum-group minerals to the source bodies, typically using stratigraphic trenching or drilling followed by continuous sampling, lithogeochemical interpretations and grid drilling (e.g., Green and Peck, 2005; Cameron and Hattori, 2005; Maier and Barnes, 2005). Geophysical methods can be used directly (e.g., IP surveys to detect PGE-rich disseminated sulfide mineralization) or indirectly (e.g., magnetic surveys for mapping igneous layering, intrusive contacts and structures) for PGE exploration (e.g., Balch, 2005). More recently,

PGE explorers are testing alternative methods such as seismic surveys (e.g., Gibson, 2011) and, in glaciated terrains, heavy indicator mineral dispersion mapping (e.g., McClenaghan, 2005).

Arguably most of the known magmatic oxide resources of chromite, vanadium-bearing magnetite and ilmenite were discovered through geological mapping and prospecting and by serendipitous finds made during exploration programs focused on other commodities. Up until now these smaller market commodities have not attracted the levels of investment from the exploration and mining sector that the other MODUM commodities have. Accordingly, it is difficult to find baseline data on historical exploration approaches for oxide MODUM. Logically, many recent discoveries of chromite, vanadium-bearing magnetite and ilmenite are extensions of known deposits. This is particularly true for magnetite-rich deposits that have easily traceable magnetic responses but it also applies to laterally extensive stratiform chromitite layers (e.g., Lower Group chromitites in the Bushveld Complex; Cawthorn et al., 2005). For ilmenite, despite significant exploration activity in the Grenville Province in Canada and parts of Scandinavia, the dominance of large and easily processed mineral sands deposits has proven to be a major impediment to bedrock ilmenite exploration.

A major pitfall for many exploration programs is an over-emphasis on specific deposit models and/or styles of mineralization. Taking a narrow view of what types of deposits to pursue or what geophysical, geochemical and geological responses are expected can result in missing concentrations of valuable minerals or mineralization styles that are not specifically being targeted. A major recommendation arising from the current analysis of global MODUM resources is that a much broader-based approach to exploration in mafic to ultramafic magmatic provinces is warranted and is more likely to lead to valuable mineral discoveries than the traditional, commodity-specific and model-driven approaches. Risk-constrained exploration programs that match the abilities (technical, financial) of the explorer can now consider the full spectrum of MODUM using a fairly standard set of tools. To this end, some common challenges in MODUM exploration philosophies and methodologies are listed below in the hope that future explorers can recognize them in the early planning stages and thereby optimize the opportunities for making significant discoveries:

- intrusions hosting stratiform reef-type PGE deposits are not generally considered to be prospective for massive copper–nickel sulfide deposits; however, this is somewhat a self-fulfilling prophecy that is

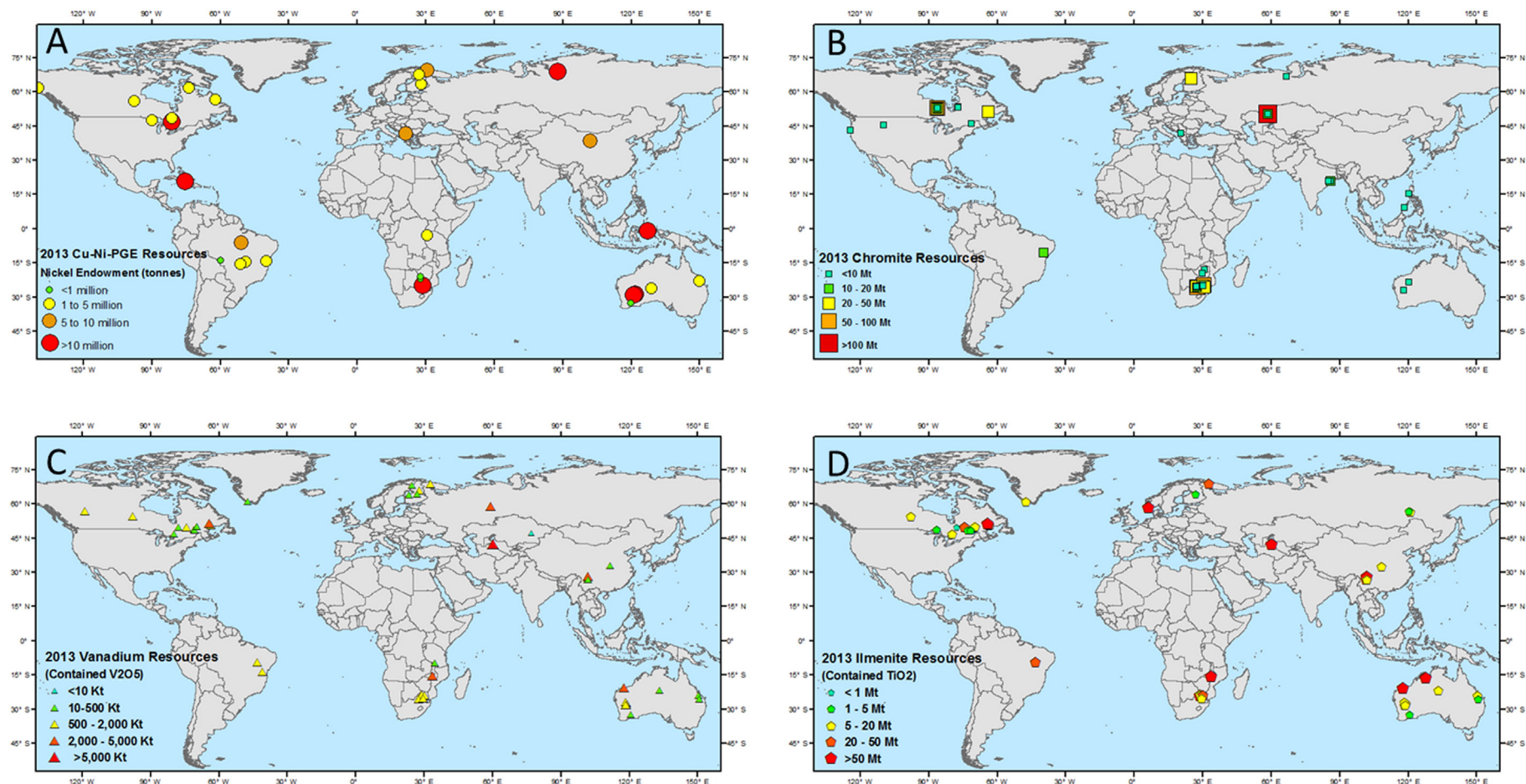


Fig. 18. Geographic distribution of contained metal value (for nickel deposits) or contained chromite or metal oxide (for oxide deposits) for MODUM resources and reserves. A. Total contained metal nickel estimated for the top 25 key nickel belts based on the sum of historical production and 2013 reserves and resources (=total nickel endowment) for MODUM nickel sulfide and laterite deposits. See Table 8 for source data. B. 2013 global chromite resources. C. 2013 global MODUM-related vanadium resources expressed as contained V_2O_5 . D. 2013 global MODUM-related ilmenite resources expressed as contained TiO_2 .

challenged by the discovery of semi-massive and massive sulfide mineralization in PGE reef environments, including the northern lobe of the Bushveld Complex where massive Ni–Cu sulfide mineralization occurs in close proximity to the Platreef PGE deposits at both Anglo American's Mogalakwane mine and Ivanhoe Platinum's Platreef deposit (e.g., Buchanan et al., 1981; Kinnaird et al., 2005)

- stratiform and stratabound copper–nickel sulfide deposits are commonly believed to lack the size and grade needed to support profitable extraction; this is challenged by new resources developed in the Duluth Complex, USA (Miller et al., 2002) and in the Santa Rita deposit, Brazil (Barnes et al., 2011)
- chromite deposits are commonly understood to be restricted to giant layered ultramafic complexes (e.g., Cawthorn et al., 2005) or podiform deposits in certain types of ophiolite complexes (e.g., Lago et al., 1982); this view is challenged by recent discoveries in the "Ring of Fire" district, northern Ontario (Laarman, 2014)
- economically attractive vanadium-rich magnetite deposits are similarly commonly believed to be restricted to 'giant' layered complexes such as the Windimurra Complex in Western Australia (Atlantic Ltd., 2015) and the Bushveld Complex; this is challenged by Largo Resources' Maracas mine project in Brazil (<http://www.largoresources.com/English/projects/maracas/>)
- magmatic ilmenite concentrations of economic interest are generally believed to relate to Proterozoic anorthositic massifs such as those in the Grenville Province in Quebec (Corriveau et al., 2007); this is challenged by high-grade ilmenite deposits in oxide-ultramafic intrusions within the Duluth Complex, USA (Severson, 1995; Miller et al., 2002)
- compressional tectonic environments are typically believed to have a lower probability of hosting nickel–copper sulfide MODUM than rift-related, extensional environments; this is challenged by the discovery of the Aguablanca nickel sulfide deposit in Spain that occurs in a transpressional shear zone (Tornos et al., 2006).

Other challenges facing future MODUM explorers relate to the selection and sequencing of cost-effective and technically-effective exploration tools. Appropriate tools capable of detecting or vectoring to multiple MODUM types include airborne magnetic survey data, regional gravity survey data, surficial media geochemistry surveys and critical field-based mapping and sampling. Effective field-based investigations require the input of experienced geoscientists that are able to make critical observations including the selection of representative samples of both weathered and fresh mafic to ultramafic rocks to allow initial assessment of prospectivity for different types of MODUM. Some less established but highly effective initial exploration tools include:

- lithogeochemical screening to identify fertile magmatic suites and vector to nearby deposits, as is common practice for magmatic copper–nickel sulfide programs, but not commonly applied to oxide MODUM (e.g., Lightfoot, 2007; Naldrett, 2004)
- dispersion mapping of indicator minerals for all types of MODUM in glaciated terrains (e.g., McClenaghan, 2005)
- collection of precision age determinations to define the geographical extent of a specific magmatic province or discrete magmatic episodes within a province (often assumed but not commonly tested) (e.g., Ernst, 2014)
- early investment into applied mineralogical analyses and bench-scale metallurgical testing to determine ore and gangue mineral compositions and textures and amenability to traditional processing routes (e.g., Huminicki et al., 2011; Hoal et al., 2006).

Early and sustained investment in data compilation, integration and spatial analysis (targeting) by qualified personnel is often under-emphasized in MODUM exploration, especially in the junior exploration sector where pressure from financiers for a quick return on investment can lead to incomplete initial technical due diligence. It is at the initial

targeting stage for a new exploration program where well intentioned and adequately funded programs can run astray. Effective target selection requires expert knowledge and access to a large amount of geographical, geochemical, geophysical and geological data. Taking the time to define, compile and organize an often overwhelming amount of relevant information is critical to success. And having the right team to analyze the data is equally important. The optimal targeting team should include both experienced generalist explorers and technical specialists.

In addition to prospectivity, the selection of where to invest exploration capital is typically based on security and regulatory risk tolerance, cultural and geological familiarity, land positioning and, for producers, the location of existing operations. For MODUM, most of the world's cratons and many internal and external orogenic belts are prospective for both sulfide and oxide deposits so the decision on where to explore is not straight forward. In contrast, nickel–cobalt laterite deposits are generally confined between the mid latitudes in both hemispheres (Marsh and Anderson, 2011). Working from known, established key mineral belts to underexplored but temporally and genetically equivalent frontier or grassroots environments is a sensible, recommended approach that is becoming more effective as the understanding of the relationship between large mantle-derived magmatic events (large igneous provinces), MODUM and continental break ups improves (Ernst, 2014). Furthermore, areas where two or more styles of MODUM exist in the same crustal segment or magmatic province provide an ideal starting point for area selection.

Figs. 19 and 20 include two overview thematic maps showing known areas of coincident MODUM types for both the western (Fig. 19) and eastern (Fig. 20) hemispheres. In Africa, the Kaapvaal craton in South Africa and Botswana hosts numerous copper–nickel–PGE sulfide deposits, chromite deposits and vanadium-bearing magnetite deposits (Fig. 19). Most of these deposits are associated with the Bushveld Complex (Cawthorn et al., 2005) and its satellite bodies (e.g., Uitkomst Complex; Gauert, 2001). The recent renewal of grassroots exploration on lesser explored parts of the Bushveld Complex has led to new discoveries such as Platinum Group Metals' Waterberg project (<http://www.platinumgroupmetals.net/>), demonstrating that even a mature camp such as the Bushveld Complex can deliver important new discoveries with new approaches in lesser explored areas. In Zimbabwe, the Zimbabwe craton hosts several copper–nickel sulfide deposits located in Archean greenstone belts as well as the emerging Great Dyke mining district (Fig. 19). Further to the north, nickel sulfide, nickel laterite and vanadium deposits occur in an arcuate area aligned with the southern and western border regions of Tanzania (Fig. 19) within Proterozoic mobile belts along the east side of the Congo craton (Kibaran Belt) and the south side of the Tanzania craton (Ubendian Belt).

In the Nordic region of western Europe, several Archean and Proterozoic magmatic provinces host MODUM sulfide and oxide mines and resources including the Fennoscandian Shield in central Finland, the Lapland greenstone belt in northern Finland and north-western Norway and the Imandra–Varzuga belt in the Kola Peninsula, Russia (Fig. 19). The Ural Mountains in Russia host a wide range of valuable ore deposits (Herrington et al., 2005) including nickel sulfide, nickel laterite and vanadium deposits (Fig. 19). In the eastern Mediterranean region, several nickel laterite and chromite deposits occur in association with ophiolite complexes that extend from Cyprus, Turkey and Greece in the south to Serbia and Montenegro in the north (Fig. 19).

North America hosts some of the highest value copper–nickel–PGE deposits on earth, including numerous deposits in the Sudbury mining district, the Voisey's Bay deposits in Labrador (Naldrett and Li, 2007), the Raglan Belt in northern Quebec (Lesher, 2007), the Thompson Nickel Belt in Manitoba (Layton-Matthews et al., 2007), the Stillwater Complex in Montana (Todd et al., 1982) and the wide variety of magmatic sulfide deposits contained in the Mid-continent Rift System (Miller et al., 2002). Overlapping or closely adjacent oxide and sulfide MODUM occur in the eastern Grenville Province in Quebec, the Abitibi

greenstone belt in Quebec, the Archean and Proterozoic magmatic provinces of the Mid-continent region in northwestern Ontario, northern Minnesota and upper Michigan, the northwestern Superior Province and Superior Boundary Zone in Manitoba and northern Ontario and the Wyoming craton in Montana and Wyoming (Fig. 19).

Like North America, the shield region of Brazil contains numerous Archean and Proterozoic magmatic provinces and associated MODUM, including clustering of sulfide and oxide MODUM in several regions (Fig. 19). Brazil hosts some of the world's least-explored Archean-Proterozoic cratonic masses yet several clusters of MODUM have already been defined including those in the Carajas District in the south Amazon region, the Goias District in central Brazil and the Bahia Belt and Tocantins region in northeastern Brazil (Fig. 19).

In Australia, the Yilgarn Province hosts the giant nickel sulfide and nickel laterite resources of the Eastern Goldfields superterrane, the northern portion of which also hosts vanadium-bearing magnetite deposits and ilmenite occurrences associated with the Windimurra mafic to ultramafic complex (Fig. 20; Ivanic et al., 2012). In the Kimberly Ranges, both oxide and sulfide MODUM occur along the coastal region of Western Australia (Fig. 20). In central Australia, the Musgraves Province hosts Proterozoic copper–nickel–PGE sulfide deposits, nickel laterite resources and vanadium deposits, many of which are associated with the Neoproterozoic Giles Complex in the West Musgraves Province (Wingate et al., 2004; Pirajno and Hoatson, 2012). In eastern Australia, a series of Phanerozoic mobile belts host mafic to ultramafic intrusive bodies with local nickel (PGE) laterite, nickel–copper–PGE sulfide and magmatic ilmenite resources (Fig. 20).

Most of the world's 'wet' nickel laterite resources occur in the equatorial parts of Oceania and the Indonesian and Philippine archipelagos in Southeast Asia (Fig. 20; Table 1). In most cases, these resources are not associated with primary magmatic (bedrock-hosted) deposits of other MODUM types. An exception is the coincidence of nickel saprolite and chromite deposits in the western Philippines on Luzon including the Acoje nickel laterite deposit and related resources (SNL Metals and Mining, 2014a) and the Zambales chromite deposit (Stoll, 1958). Also in the general southeast Asia region, the early Mesozoic Emeishan belt located along the Panxi Rift structural corridor in southwestern China and northern Vietnam hosts world-class iron–titanium–vanadium deposits in southern part of Sichuan Province, China (e.g., Pang et al., 2010) and several operating and past-producing copper–nickel–PGE mines such as the Danba Ni–Cu–PGE mine (Zaw et al., 2002) (Fig. 20).

Although better known for its porphyry copper deposits, the Central Asian orogenic belt hosts numerous MODUM including Ni–Cu–PGE sulfide deposits in northwest China and Mongolia and nickel laterite deposits in Kazakhstan (Figure 20). This belt is highly prospective for Ni–Cu sulfide deposits and remains underexplored for all MODUM.

The concept of using spatial coincidence of different MODUM types as a primary exploration decision making tool can be further extended to capture other classes of ore deposits that are typically associated with large magmatic provinces and their mantle-tapping feeder structures. As examples, Archean greenstone belts commonly host large sulfide and oxide MODUM but are better known for mesothermal (lode) gold deposits (Robert et al., 2005) and volcanogenic massive sulfide deposits (Franklin et al., 2005). Proterozoic mafic to ultramafic magmatic provinces are commonly spatially associated with large iron ore deposits including the Carajas District in Brazil, the Labrador Trough in Canada, the Hamersley Basin in Australia and the Mid-continent Rift, USA (Clout and Simonson, 2005) and in some cases, iron–ore copper–gold deposits (e.g., Gawler craton, Australia; Williams et al., 2005; Great Bear magmatic arc, Canada; Corriveau, 2007). By including non-MODUM deposit types, MODUM explorers can further enhance the potential for making significant new discoveries, regardless of the primary commodity(ies) or deposit class(es) being sought.

The proposed multi-commodity and geographically-focused approach to MODUM exploration also provides an opportunity for long-term exploration and mining partnerships. This applies to large magmatic provinces where no single company has the interest or ability to consolidate all of the prospective mineral lands or the financial ability to sustain the type of long-lived regional exploration program that is required to unlock the value of the targeted belt. Examples of where strategic exploration partnerships are warranted are found in the world's emerging mining districts where a comprehensive understanding of the range in styles and settings of MODUM has already been partly established. Examples include:

- the Mesoproterozoic mid-continent region of central North America where very large, undeveloped disseminated copper–nickel–PGE resources in the Duluth Complex (Miller et al., 2002) are flanked by approximately coeval oxide–ultramafic titanium (vanadium) deposits (e.g., Johnson et al., 2012) and ultramafic-hosted nickel-rich magmatic sulfide deposits including Lundin's Eagle Mine in Michigan (Ding et al., 2012) and Rio Tinto's and Talon Metals Corp.'s Tamarack deposit in Minnesota (Thomas et al., 2014)
- the Permo-Triassic Emeishan magmatic province in south-western China and Vietnam, host to the giant Panzhihua iron–titanium–vanadium deposit and numerous small- to medium-size nickel–copper–PGE sulfide mines and deposits including Ban Phuc and related deposits in Vietnam (Glotov et al., 2001) and the Danba (Yangliuping) and Gaojacun deposits in Sichuan Province, China (Zaw et al., 2002)
- the Neoproterozoic Paleoproterozoic Carajas District in Brazil with its enormous copper, nickel, iron and gold resources (Laznicka, 2010)
- the Mesoproterozoic Musgraves Province in central Australia including the Giles Complex nickel–copper–PGE deposits and oxide mineral occurrences (Pirajno and Hoatson, 2012) and the prospects for new iron ore copper–gold discoveries in a similar geological environment to the Olympic Dam deposit in South Australia (Williams et al., 2005)
- the Baltic shield and adjacent, accreted Proterozoic terranes that host major bedrock ilmenite deposits in the Telnes District, Norway, numerous nickel–copper sulfide deposits and resources including the Pechenga and Monchegorsk districts in Russia and Lapland Belt in Finland (Alapieti et al., 1989), and an impressive range in non-MODUM ore deposit types including iron ore copper–gold (e.g., Norrbotten District, Sweden), lode gold (e.g., Kittila gold mine, northern Finland) and volcanogenic massive sulfide deposits (Skellefteå District, central Sweden) (Eilu, 2012).

Each of these regions is considered as a high-potential, emerging MODUM belt. Although many of the more established MODUM mining camps such as the Bushveld Complex, the Great Dyke and the Siberian flood basalt province retain excellent potential for major new discoveries, they also feature significant barriers to entry including uncertainties relating to government mining policy (e.g., ownership limits) and the lack of quality exploration properties available for staking. In contrast, most of the listed high-potential belts feature established regulatory policies that encourage new exploration investments including investment from foreign-owned companies. In most of these belts, local or federal governments also provide free or low cost access to high quality geoscientific databases.

It is also important to recognize that in some jurisdictions, including large portions of both Brazil and Australia, significant opportunities exist to concurrently explore for both laterite deposits and underlying bedrock sulfide and oxide MODUM. In both countries, the known nickel ($\pm$ cobalt $\pm$ PGE) laterite resources are commonly sourced from large ultramafic to mafic intrusions developed in Proterozoic mobile belts or in large ensialic rift structures, both of which are preferred environments for magmatic nickel–copper–PGE sulfide deposits and oxide MODUM. The fingerprint of an underlying bedrock deposit may be detectable during the course of laterite exploration by simply drilling

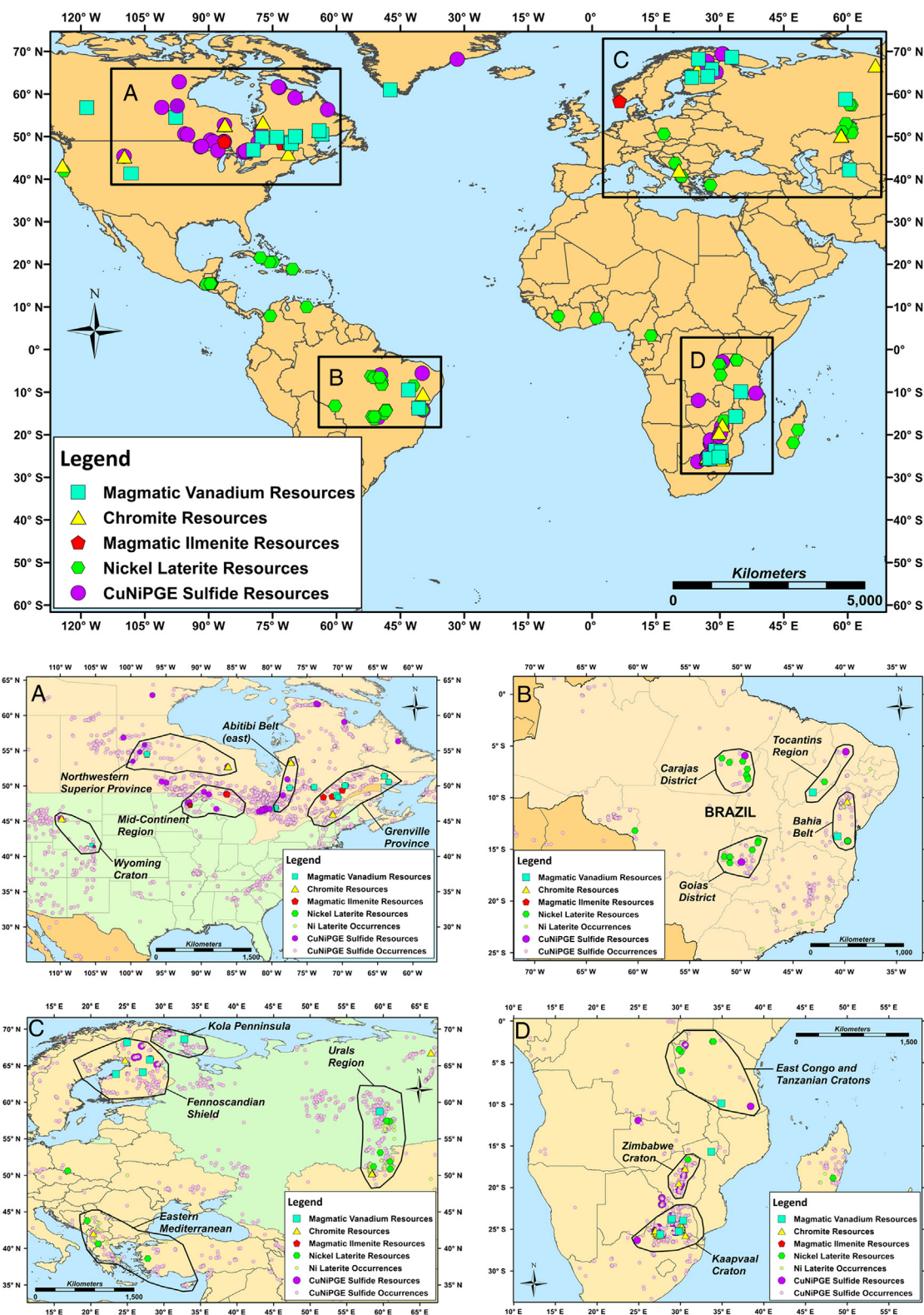


Fig. 19. Clustering of MODUM of different classes in the Western Hemisphere including Africa and Western Eurasia. Large overview map at the top of the figure provides locations for the four continent-scale maps (A–D) below. The continental maps show specific clusters of two or more MODUM deposit types within a discrete geological belt or domain. Many of these clusters are further supported by the location of Ni–Cu sulfide occurrences derived from published global mineral occurrence data from United States Geological Survey and the Geological Survey of Canada. See text for discussion of the deposit clusters identified on the figure.

through the laterite profile and/or using resistive indicator minerals (either their abundance or aspects of their mineral chemistry). Good examples of areas having both laterite and sulfide MODUM exploration potential in the same intrusive body include the Santa Rita deposit in

Bahia State, Brazil (Barnes et al., 2011) and the enormous Niquelandia Complex in Goias State, Brazil that hosts the Barro Alto and Tocantins nickel laterite mining operations and numerous chromite, PGE and copper–nickel occurrences (Ferreira Filho, 1995).

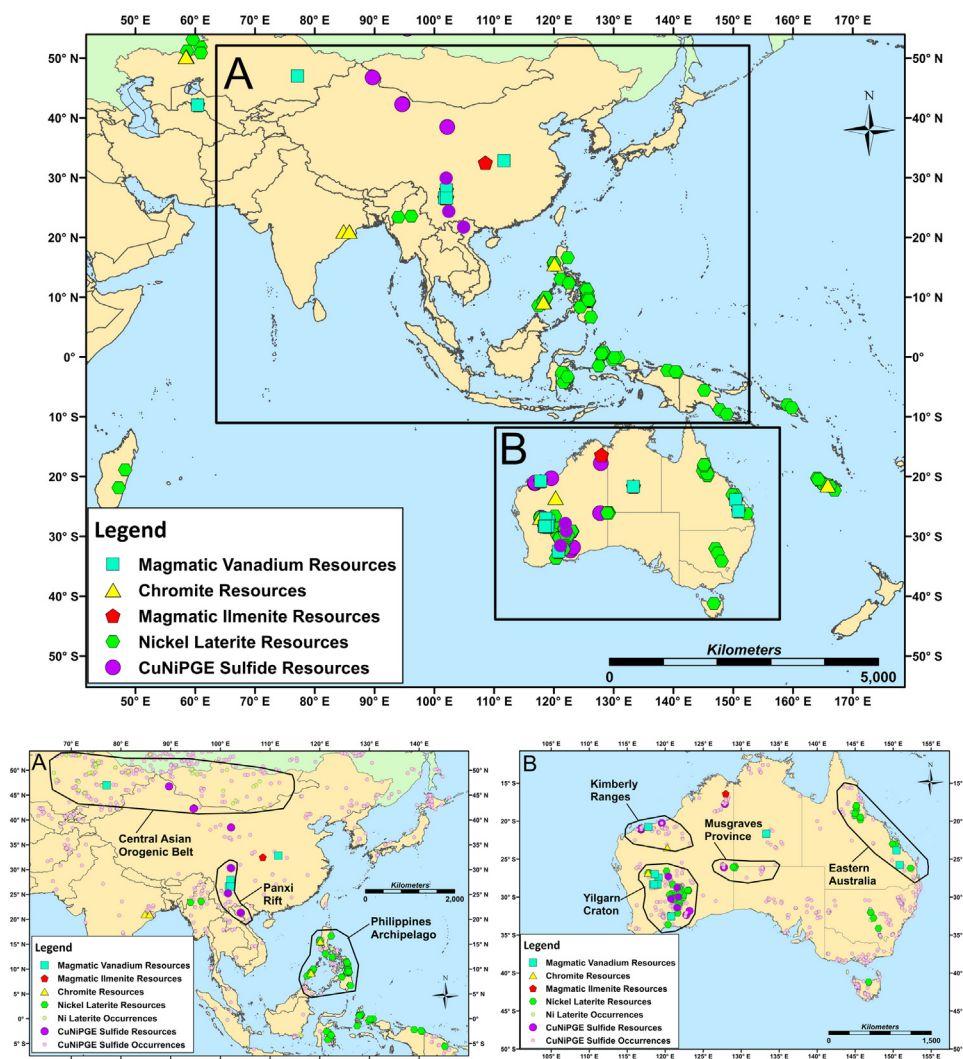


Fig. 20. Clustering of MODUM of different classes in the Eastern Hemisphere excluding Africa and Europe. Large overview map at the top of the figure provides locations for the two continent-scale maps (A–B) below. The continental maps show specific clusters of two or more MODUM deposit types within a discrete geological belt or domain. Many of these clusters are further supported by the location of Ni–Cu sulfide occurrences derived from published global mineral occurrence data from United States Geological Survey and the Geological Survey of Canada. See text for discussion of the deposit clusters identified on the figure.

After establishing where to explore and what primary commodities are being sought, the following general methodology for MODUM exploration is recommended:

1. Regional desk-top targeting involving a detailed analysis of 2D and 3D potential field data (gravity, magnetics) and regional geochemical surveys (e.g., till, lake sediment, stream sediment, lag soil) to define the aerial extent and depth limits of the targeted magmatic province and the location of structurally attractive features such as intersecting major crustal-scale structures that could have focused heat and magma during mafic to ultramafic magmatism.
2. Assessment of the known styles of mineralization meeting corporate value expectations in order to establish property-scale exploration methodologies, including, but not limited to: detailed airborne or ground magnetic-electromagnetic-resistivity-radiometric-gravity surveys; seismic surveys (rarely utilized); detailed surface media geochemical surveys (e.g., percussion drilling in areas with extensive residual soil cover or base of till surveys in glaciated terranes); lithological and structural mapping; and, early 'stratigraphic' drilling to confirm the existence of prospective rock types and structures.
3. Lithogeochemical screening and vectoring using outcrop and drill

core samples. Recent advances in analytical precision and a progressive lowering of detection limits for key pathfinder elements has improved the reliability and lowered the costs of lithogeochemical exploration methods. These methods include the following: the recognition of the signature of magmatic events that have developed and deposited immiscible metal-rich magmatic sulfide liquid (Arndt et al., 2005; Naldrett, 2004); the determination of fractionation trends that could lead to saturation in oxide ore minerals (Cawthorn et al., 2005); the mantle source characteristics that could play a major role in determining prospectivity for PGE (Hamlyn and Keays, 1986); and, the extent to which assimilation of crustal rocks has altered the crystallization trajectory – possibly triggering sulfide or oxide nucleation beyond what would otherwise have occurred (Barnes, 2006; Barnes and Lightfoot, 2005; Eckstrand and Hulbert, 2007; Irvine, 1975). The importance of semi-metals such as arsenic, tellurium, bismuth and antimony in concentrating precious metals in MODUM is also becoming a viable lithogeochemical exploration tool with significant, recent improvements to the analytical cost and detection limits for these elements. Lithogeochemical vectoring for PGE-rich stratiform deposits has long been applied in routine property-scale exploration, and with good success. However,

screening and vectoring for oxide-related and base metal sulfide-rich MODUM has seen less emphasis. This reflects the preference for using geophysical surveys for direct detection of oxide mineralization and, possibly, a lack of appropriate understanding of the potential power of lithogeochemical exploration methods for oxide MODUM. The signature of all the geochemical and mineralogical changes that take place in a magmatic system over the duration of a magmatic event are recorded in the various crystallization products – including rocks, minerals and trapped volatile phases. A predictive lithogeochemical model for a selected magmatic suite capable of assessing the sulfur saturation and oxide saturation status in both 2D and 3D space is something that will benefit all future MODUM explorers.

4. Systematic and intensive target drilling guided by appropriate, high-resolution and deep-penetrating geophysical surveys and augmented by detailed surficial media geochemical surveys and lithogeochemical and mineralogical studies on drill core samples (vectoring), with drilling extending to the full depth range supported by the expected deposit value being explored for.

The known classes of MODUM capture a large range in geological settings including: ophiolite belts (podiform chromitite and nickel-cobalt laterite deposits); sub-vertical feeder-dykes (both chromite and nickel-copper-PGE sulfide deposits); contact-related (internal or external to host body) disseminated to massive nickel-copper-PGE sulfide deposits; stratabound reef-type deposits of PGE, chromite, vanadium-bearing magnetite and ilmenite; and late, discordant pipe-like bodies saturated in sulfide and/or oxide. Naldrett et al. (1990) and Naldrett (2004) attempted to encapsulate this diverse range of MODUM deposits in a single schematic diagram, focussing on copper, nickel, chromite and PGE mineralization styles and sites. This diagram can now be extended to include the known styles of magmatic titanium and vanadium-rich magnetite deposits and preferred sites for nickel, cobalt and PGE laterite development. Risk mitigation efforts for future MODUM explorers should include a broader-based approach to what should be explored for (oxide and sulfide mineralization and weathering products) and what tools should be applied. Optimal targets are found in the world's emerging mineral districts that feature overlapping styles of MODUM, favorable regulatory policies and access to underexplored mineral properties. New MODUM exploration targets will likely emerge from ongoing investigations into the role of large igneous provinces in continental break-up events (Ernst, 2014).

7. Conclusions

Magmatic ore deposits associated with ultramafic and mafic magmatism generated ~\$70 billion of value from mine production in 2013, representing ~7% of total global metal and mineral mine output (excluding fossil fuels). In terms of total historical and current mineral endowment the largest key mineral belts for MODUM are the Bushveld Complex (~\$3.6 trillion), the Norilsk–Talnakh mining district (~\$1.3 trillion) and the Indonesian Archipelago laterite belt (\$0.7 trillion). These MODUM districts rival the world's largest mineral camps including the Central Andean porphyry copper district, the Witwatersrand basin gold mining district, the Zambian copper belt and the Carajas iron ore district (Laznicka, 2010). The significant value of many MODUM districts coupled with the increased stability and size of key MODUM-related commodity markets (e.g., nickel, chromite, PGE) provides a strong incentive for increased exploration investment in the world's major mafic to ultramafic magmatic provinces. For explorers, the diversity of valuable magmatic ore deposits that should be considered covers most of earth's history, cratonic masses, orogenic belts, climate zones and physiographic regions. High-value resources associated with mafic to ultramafic magmatic bodies that are known to support excellent operating margins and long life operations include several styles of chromite mineralization, many massive

nickel ($\pm$ copper) sulfide deposits, most nickel saprolite deposits, several styles of PGE mineralization, several vanadium-bearing magnetite deposits and a few magmatic ilmenite deposits. Despite having similar or higher average net smelter return value mineralization, large tonnage, disseminated, polymetallic nickel-copper-PGE sulfide deposits have yet to attract the attention of most of the world's large copper and PGE mining companies. Nonetheless the opportunity exists to apply large-scale mining methods to improve the economics for these deposits in the same way that bulk mining transformed the copper mining industry with economy of scale innovations at large porphyry copper mining projects in the 1980s and 1990s.

A comprehensive understanding of nickel, copper, cobalt, PGE, chromite, ilmenite and vanadium commodity markets is considered as a critical first step for future explorers to develop more effective strategies for delivering valuable new mineral discoveries in mafic to ultramafic magmatic provinces. Emerging mineral districts that have favorable risk and prospectivity rating and that contain multiple styles of mafic to ultramafic magmatic mineral deposits are considered to be the premier destinations for future exploration programs. A broad-based approach to exploration for mafic to ultramafic magmatic ore deposits that recognizes the potential for different styles of mineralization within a single magmatic province is far more likely to generate valuable discoveries than commonly used, narrowly-focused strategies. Although frontier belts hold greater promise for major, near-surface discoveries, established mineral districts can yield significant new discoveries by applying modern exploration methodologies, extending the search area to deeper crustal levels and exploring for a wider range of deposit types. Current supply and demand trends appear highly favorable for most of the economic metals and minerals associated with magmatic ore deposits associated with mafic to ultramafic magmatism. Strong, long-term demand growth for alloying metals such as nickel, chromium and vanadium and for the platinum-group elements as both a direct investment vehicle and as industrial metals bodes well for companies engaged in exploration and mining of this important class of ore deposit.

Conflict of interest

The author's of this manuscript are not aware of any conflicts of interest with regard to the content or publication of the content of this manuscript.

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Appendix A. Supplementary data

Supplementary data to this article (Appendix 1 and Appendix 2) can be found online at <http://dx.doi.org/10.1016/j.oregeorev.2015.06.004>.

References

- Alapieti, T.T., Kujanpää, J., Lahti-Nen, J.J., Papunen, H., 1989. The Kemi stratiform chromitite deposit, northern Finland. *Econ. Geol.* 84, 1057–1077.
- Ames, D., Farrow, C.E.G., 2007. Metallogeny of the Sudbury mining camp, Ontario. Geological Association of Canada, Special Publication No. 5. Mineral Deposits of Canada. A Synthesis of Major Deposit Types, District Metallogeny, The Evolution of Geological Provinces and Exploration Methods, pp. 329–350.
- Arndt, N.T., Leshner, C.M., Czamanske, G.K., 2005. Mantle-derived magmas and magmatic Ni–Cu–(PGE) deposits. *Economic Geology*, One Hundredth Anniversary Volume, pp. 5–24.
- Arsenault, D., Hennessey, B.T., Oliveira, H.L., Spooner, J., Tanas, K., Weston, S., 2013. NI 43-101F Technical Report: preliminary economic assessment of the Maracas vanadium project, 1.4 million tonnes per year processing plant. Prepared for Largo Resources Ltd. by Runge Pincock Minarco, March 4, 2013 (401 pp.).
- Atlantic Ltd., 2015. Windimurra Project. <http://atlanticltd.com.au/projects/windimurra>.
- Bai, Z.J., Zhong, H., Naldrett, A.J., Zhu, W.G., Xu, G.W., 2012. Whole-rock and mineral composition constraints on the genesis of the Giant Hongge Fe–Ti–V oxide deposit in the Emeishan Large Igneous Province, Southwest China. *Econ. Geol.* 107, 507–524.
- Balch, 2005. The geophysical signatures of PGE deposits. Exploration for Platinum-group Element Deposits. Mineralogical Association of Canada, Short Course Series v. 35, pp. 275–285.
- Balch, S.J., Crebs, T.J., King, A., Verbiski, M., 1998. Geophysics of the Voisey's Bay Ni–Cu–Co deposits. SEG Technical Program Expanded Abstracts 1998, pp. 784–787.
- Barnes, S.J., 2006. Komatiite-hosted nickel sulfide deposits: geology, geochemistry and genesis. *Soc. Econ. Geol. Spec. Publ.* 13, 51–97.
- Barnes, S.-J., Lightfoot, P.C., 2005. Formation of magmatic nickel sulfide ores and processes affecting their copper and platinum group element contents. *Economic Geology*, One Hundredth Anniversary Volume, pp. 179–214.
- Barnes, S.J., Osborne, G.A., Cook, D., Barnes, L., Maier, W.D., Godel, B., 2011. The Santa Rita nickel sulfide deposit in the Fazenda Mirabela intrusion, Bahia, Brazil: geology, sulfide geochemistry and genesis. *Econ. Geol.* 106, 1083–1110.
- Buchanan, D.L., Nolan, J., Suddaby, P., Rouse, J.E., Viljoen, M.J., Davenport, J.W.J., 1981. The genesis of sulfide mineralization in a portion of the Potgietersrus Limb of the Bushveld Complex. *Econ. Geol.* 76, 568–579.
- Butt, C.R.M., 2004. Geochemical dispersion, process and exploration models. *Regolith Expression of Australian Ore System – A Compilation of Geochemical Case Histories and Conceptual Models*. CRC Landscape Environment and Mineral Exploration Monograph, Canberra, Australia, pp. 81–106.
- Cameron, E.M., Hattori, K.H., 2005. PGE in geochemical exploration. Exploration for Platinum-Group Element Deposits. Mineralogical Association of Canada, Short Course Series v. 35, pp. 287–307.
- Canadian Institute of Mining, 2010. Definition standards for mineral resources and mineral reserves. CIM Standing Committee on Reserve Definitions (10 pp.).
- Cawthorn, R.G., Barnes, S.J., Ballhaus, C., Malitch, K.N., 2005. Platinum group element, chromium and vanadium deposits in mafic and ultramafic rocks. *Economic Geology*, One Hundredth Anniversary Volume, pp. 215–250.
- Charlier, B., Olivier, N., Malpas, S., de Marneffe, C., Duchesne, J.-C., Auwera, J.V., Bolle, O., 2010. Origin of the giant Allard Lake ilmenite ore deposit (Canada) by fractional crystallization, multiple magma pulses and mixing. *Lithos* 117, 119–134.
- Clout, J.M.F., Simonson, B.M., 2005. Precambrian iron formations and iron formation-hosted iron ore deposits. *Economic Geology*, One Hundredth Anniversary Volume, pp. 643–680.
- Connolly, E., Orsmond, D., 2011. The mining industry: from bust to boom. *Economic Analysis Department, Reserve Bank of Australia* pp. 111–156.
- Corriveau, L., 2007. Iron oxide copper–gold deposits: a Canadian perspective. Geological Association of Canada, Special Publication No. 5. Mineral Deposits of Canada. A Synthesis of Major Deposit Types, District Metallogeny, The Evolution of Geological Provinces and Exploration Methods, pp. 307–328.
- Corriveau, L., Perreault, S., Davidson, A., 2007. Prospective metallogenic settings of the Grenville Province. Geological Association of Canada, Special Publication No. 5. Mineral Deposits of Canada. A synthesis of major deposit types, district metallogeny, the evolution of geological provinces and exploration methods, pp. 819–848.
- Cox, D.P., Singer, D.A. (Eds.), 1986. Mineral Deposit Models. United States Geological Survey Bulletin.
- Ding, X., Ripley, E.M., Li, C., 2012. PGE geochemistry of the Eagle Ni–Cu–(PGE) deposit, Upper Michigan: constraints on ore genesis in a dynamic magma conduit. *Mineral. Deposita* 47, 89–104.
- Eckstrand, O.R., Hulbert, L., 2007. Magmatic nickel–copper–platinum group element deposits. Geological Association of Canada, Special Publication No. 5. Mineral Deposits of Canada. A synthesis of major deposit types, district metallogeny, the evolution of geological provinces and exploration methods, pp. 205–222.
- Eilu, P., 2012. Mineral deposits and metallogeny of Fennoscandia. Geological Survey of Finland, Special Paper 53 (401 pp.).
- Elias, M., 2002. Nickel laterite deposits—geological overview, resources and exploration. *Giant Ore Deposits – Characteristics, Genesis, and Exploration* University of Tasmania, CODES Special Publication 4 pp. 205–220.
- Ernst, R.E., 2014. Large Igneous Provinces. Cambridge University Press (661 pp.).
- Ferreira Filho, C.F., 1995. Niquelandia mafic–ultramafic layered complex, north-Goiás, Brazil: petrology, age and potential for PGE ore deposits (Ph.D. thesis). University of Toronto.
- Force, E.R., 1991. Geology of titanium–mineral deposits. Geological Society of America, Special Paper 259 (112 pp.).
- Franklin, J.M., Gibson, H.L., Jonasson, I.R., Galley, A.G., 2005. Volcanogenic massive sulfide deposits. *Economic Geology*, One Hundredth Anniversary Volume, pp. 523–560.
- Gauert, C., 2001. Sulfide and oxide mineralisation in the Uitkomst Complex, South Africa: origin in a magma conduit. *J. Afr. Earth Sci.* 32, 149–161.
- Gibson, M.A.S., 2011. Application of seismic to mineral deposit exploration and evaluation. Society of Exploration Geophysicists 30. The Leading Edge, pp. 616–621.
- Glotov, A.I., Polyakov, G.V., Hoa, T.T., Balykin, P.A., Akimov, V.A., Krivenko, A.P., Tolstykh, N.D., Phuong, N.T., Thanh, H.H., Hung, T.Q., Petrova, T.E., 2001. The Ban Phuc Ni–Cu–PGE deposit related to the Phanerozoic komatiite–basalt association in the Song Da rift, northwestern Vietnam. *Can. Mineral.* 39, 573–589.
- Golightly, J.P., 2010. Progress in understanding the evolution of nickel laterites. In: Goldfarb, R.J., Marsh, E.E., Monecke, T. (Eds.), *The Challenge of Finding New Mineral Resources – Global Metallogeny, Innovative Exploration, and New Discoveries*. Society of Economic Geologists Special Publication 15, pp. 451–485.
- Green, A., Peck, D., 2005. PGE exploration: economic considerations and geological criteria. Exploration for Platinum-Group Element Deposits. Mineralogical Association of Canada, Short Course Series 35, pp. 247–274.
- Hamlyn, P.R., Keays, R.R., 1986. Sulfur saturation and second-stage magmas: application to the Bushveld platinum metal deposits. *Econ. Geol.* 81, 1431–1445.
- Hanson, K., Orbock III, E.J.C., Hertel, M., Drozd, M., 2011. NI 43-101 Technical Report: Feasibility Study – Gibellini Vanadium Project. Prepared for American Vanadium Corp. by AMEC, August 31, 2011 (235 pp.).
- Herrington, R.J., Zaykov, V.V., Maslennikov, V.V., Brown, D., Puchkov, V.N., 2005. Mineral deposits of the Urals and links to geodynamic evolution. *Economic Geology*, One Hundredth Anniversary Volume, pp. 1069–1096.
- Hitzman, M., Kirkham, R., Broughton, D., Thorson, J., Selley, D., 2005. The sediment-hosted stratiform copper ore system. *Economic Geology*, One Hundredth Anniversary Volume, pp. 609–642.
- Hoal, K., McNulty, T.P., Schmidt, R., 2006. Metallurgical advances and their impact on mineral exploration and mining. *Economic Geology*, Special Publication 12, pp. 243–261.
- Huminicki, M.A.E., Sylvester, P.J., Shaffer, M., Wilton, D.H.C., Evans-Lamswood, D., Wheeler, R.I., 2011. Systematic and integrative ore characterization of massive sulfide deposits: an example from Voisey's Bay Ni–Cu–Co ovoid orebody, Labrador, Canada. *Explor. Min. Geol.* 20, 53–82.
- Indian Minerals Yearbook. Indian Bureau of Mines.
- Irvine, T.N., 1975. Crystallization sequences in the Muskox intrusion and other layered intrusions – 2. Origin of chromitite layers and similar deposits of other magmatic ores. *Geochim. Cosmochim. Acta* 39, 991–1020.
- Ivanic, J., Wingate, M.T.D., Kirkland, C.L., Van Kranendonk, M.J., Wyche, S., 2012. Age and significance of voluminous mafic–ultramafic magmatic events in the Murchison Domain, Yilgarn Craton. *Aust. J. Earth Sci.* 57, 597–614.
- Jobin-Bevans, L.S., 1997. Geology, mineral chemistry and petrogenesis of the Pipestone Lake anorthosite complex (M.Sc. thesis), University of Manitoba (392 pp.).
- Johnson, M., Farrow, D., Barnett, W., 2012. NI 43-101 Technical Report on the Longnose Ilmenite Project, Minnesota, USA. Prepared for Cardero Resource Corp. by SRK Consulting, January 27, 2012 (96 pp.).
- King, A., 2007. Review of geophysical technology for Ni–Cu–PGE deposits. Proceedings of Exploration 07: Fifth Decennial International Conference on Mineral Exploration, pp. 647–665.
- Kinnaird, J.A., Hutchison, D., Schurmann, L., Nex, P.A.M., de Lange, R., 2005. Petrology and mineralisation of the southern Platreef: northern limb of the Bushveld Complex, South Africa. *Mineral. Deposita* 40, 576–597.
- Laarman, J.E., 2014. A detailed metallogenic study of the McFaulds Lake chromite deposits, northern Ontario (Ph.D. thesis), University of Western Ontario (510 pp.).
- Lago, B.L., Rabinowicz, M., Nicolas, A., 1982. Podiform chromite ore bodies: a genetic model. *J. Petrol.* 23, 103–125.
- Layton-Matthews, D., Leshner, C.M., Burnham, O.M., Liwanig, J., Halden, N.M., Hulbert, L., Peck, D.C., 2007. Magmatic Ni–Cu–platinum-group element deposits of the Thompson Nickel Belt. Mineral Deposits of Canada. Geological Association of Canada, Special Publication 5, pp. 409–432.
- Laznicka, P., 2010. Giant metallic deposits. second edition. Springer-Verlag, Berlin Heidelberg (949 pp.).
- Leshner, C.M., 2007. Ni–Cu–(PGE) deposits in the Raglan area, Cape Smith Belt, New Quebec. Mineral Deposits of Canada. Geological Association of Canada, Special Publication 5, pp. 351–386.
- Lightfoot, P.C., 2007. Advances in Ni–Cu–PGE sulphide deposit models and implications for exploration technologies. Proceedings of Exploration 07: Fifth Decennial International Conference on Mineral Exploration, pp. 629–646.
- Maier, W.D., Barnes, S.-J., 2005. Exploration for Platinum-Group Element Deposits. Mineralogical Association of Canada, Short Course Series v. 35, pp. 309–341.
- Marsh, E.E., Anderson, E.D., 2011. Ni–Co laterite deposits: United States Geological Survey Open-File Report 2011-1259 (9 pp.).
- Johnson Matthey, 2013. Platinum 2013. Interim Review (40 pp.).
- McClenaghan, M.B., 2005. Indicator mineral methods in mineral exploration. *Geochem. Explor., Environ., Anal.* 5, 233–245.

- Miller Jr., J.D., Green, J.C., Severson, M.J., Chandler, V.W., Hauck, S.A., Peterson, D.M., Wahl, T.E., 2002. Geology and mineral potential of the Duluth Complex and related rocks of north-eastern Minnesota: Minnesota Geological Survey, Report of Investigations 58 (207 pp.).
- Mudd, G.M., 2010. Global trends and environmental issues in nickel mining: sulfides versus laterites. *Ore Geol. Rev.* 38, 9–26.
- Mudd, G.M., 2012. Key trends in the resource sustainability of platinum group elements. *Ore Geol. Rev.* 46, 106–117.
- Mudd, G.M., Jowitt, S.M., 2014. A detailed assessment of global nickel resource trends and endowments. *Econ. Geol.* 109, 1813–1841.
- Mudd, G.M., Weng, Z., Jowitt, S.M., 2013. A detailed assessment of global Cu resource trends and endowments. *Econ. Geol.* 108, 1163–1183.
- Naldrett, A.J., 2004. Magmatic Sulfide Deposits. *Geology, Geochemistry and Exploration*. Springer-Verlag, Berlin Heidelberg (727 pp.).
- Naldrett, A.J., Li, C., 2007. The Voisey's Bay Deposit, Labrador. Geological Association of Canada, Special Publication No. 5. Mineral Deposits of Canada. A synthesis of major deposit types, district metallogeny, the evolution of geological provinces and exploration methods, pp. 387–408.
- Naldrett, A.J., Brugmann, G.E., Wilson, A.H., 1990. Models for the concentration of PGE in layered intrusions. *Can. Mineral.* 28, 389–408.
- Naldrett, A.J., Fedorenko, V.A., Asif, M., Sushen, L., Kumilov, V.E., Stekhin, A.I., Lightfoot, P.C., Gorbachev, N.S., 1996a. Controls on the composition of Ni–Cu sulfide deposits as illustrated by those at Noril'sk, Siberia. *Econ. Geol.* 91, 751–773.
- Naldrett, A.J., Keats, H., Sparkes, K., Moore, R., 1996b. Geology of the Voisey's Bay Ni–Cu–Co deposit, Labrador, Canada. *Explor. Min. Geol.* 5, 169–179.
- Nimmo, M., 2013. Updated NI 43-101 Technical Report. Clarion–Clipperton Zone Project, Pacific Ocean. Tonga Offshore Mining Ltd. (104 pp.).
- Pang, K.-N., Zhou, M.-F., Qi, L., Shellnutt, J.G., Wang, C.Y., Zhao, D., 2010. Magmatic Fe–Ti–V oxide deposits in the Emeishan large igneous province, SW China. *Lithos* 119, 123–126.
- Papp, J.F., Lipin, B.R., 2006. Chromite. *Industrial Minerals and Rocks – Commodities, Markets, and Uses*, 7th edition Society for Mining, Metallurgy, and Exploration, Inc., Littleton, Colorado, pp. 309–333.
- Pirajno, F., Hoatson, D.M., 2012. A review of Australia's Large Igneous Provinces and associated mineral systems: implications for mantle dynamics through geological time. *Ore Geol. Rev.* 48, 2–54.
- Robert, F., Poulsen, H.K., Cassidy, K.F., Hodgson, C.J., 2005. Gold metallogeny of the Superior and Yilgarn cratons. *Economic Geology, One Hundredth Anniversary Volume*, pp. 1001–1034.
- Severson, M.J., 1995. Geology of the southern portion of the Duluth Complex. Minnesota Natural Resources and Research Institute, Technical Report 95/26 (196 pp.).
- Shi, B., 1995. Geochemistry and mineralisation of primary and secondary platinum-group elements in the ultramafic “Alaskan-type” Owendale complex and laterites in the Fifield Region, New South Wales, Australia (PhD thesis). School of Earth Sciences, The University of Melbourne.
- Sillitoe, R.H., Perello, J., 2005. Andean copper province: tectonomagmatic settings, deposit types, metallogeny, exploration and discovery. *Economic Geology, One Hundredth Anniversary Volume*, pp. 845–890.
- Simpson, R.G., 2014. Mineral Resource Estimate on the Wellgreen PGM–Ni–Cu Project. NI 43-101 Technical Report prepared for Wellgreen Platinum Ltd. (111 pp.).
- SNL Metals and Mining, 2014a. Online Mineral Resource Database as of April, 2014. www.snl.com/Metals.
- SNL Metals and Mining, 2014b. Online Database of Mineral Exploration Budget Trends for Copper, Nickel, Platinum, Palladium, Gold as of April, 2014. www.snl.com/Metals.
- Snow, G.G., Juhas, A.P., 2002. Trends and forces in mining and mineral exploration. *Soc. Econ. Geol. Spec. Publ.* 9, 1–16.
- Stillwater Mining Company, 2013. Annual Report.
- Stoll W.C., 1958. Geology and petrology of the Masinloc chromite deposit Zambales, Luzon, Philippine Islands. *Geol. Soc. Am. Bull.* 69, 419–448.
- Thomas, B., Palmer, P., Khorakchy, M.O., 2014. First independent Technical Report on the Tamarack North Project, Tamarack, Minnesota. N.I. 43-101 Technical Report Prepared for Talon Metals Corp. (147 pp.).
- Tilton, J.E., 2006. Depletion and the long-run availability of mineral commodities. *Economic Geology, Special Publication* 12, pp. 61–70.
- Todd, S.G., Keith, D.W., LeRoy, L.W., Schissel, D.J., Mann, E.L., Irvine, T.N., 1982. The J-M platinum–palladium reef of the Stillwater Complex, Montana: I. Stratigraphy and petrology. *Econ. Geol.* 77, 1454–1480.
- Tornos, F., Galindo, C., Casquet, C., Pevida, L.R., Martínez, C., Martínez, E., Iriando, A., 2006. The Aguablanca Ni–(Cu) sulfide deposit, SW Spain: geologic and geochemical controls and the relationship with a midcrustal layered mafic complex. *Mineral. Deposita* 41, 737–769.
- Annual Report. Stillwater Mining Company (127 pp.).
- United States Geological Survey, 2013. Minerals Yearbook. Volume 1. Metals and Minerals. <http://minerals.usgs.gov/minerals/pubs/commodity/myb/>.
- United States Geological Survey, 2014a. Chromium. *Mineral Commodity Summaries*, pp. 42–43 (February).
- United States Geological Survey, 2014b. Titanium mineral concentrates. *Mineral Commodity Summaries*, pp. 172–173 (February).
- Watts, A., 1997. Exploring for nickel in the 90's, or 'Til Depth us do Part'. *Proceedings of Exploration Vol. 97*, pp. 1003–1014.
- Williams, P.J., Barton, M.D., Johnosn, D.A., Fontobe, L., De Haller, A., Geordie, M., Oliver, N.H.S., Marschik, R., 2005. Iron oxide copper–gold deposits: geology, space-time distribution and possible modes of origin. *Economic Geology, One Hundredth Anniversary Volume*, pp. 371–406.
- Wingate, T.D., Pirajno, F., Morris, P.A., 2004. Warakuna large igneous province: a new Mesoproterozoic large igneous province in west-central Australia. *Geology* 32, 105–108.
- Wolffgram, P., Golden, H., 2001. Airborne EM applied to sulphide nickel – examples and analysis. *Explor. Geophys.* 32, 136–140.
- Zaw, K., Bruce, E., Burrett, C., Berry, R., Large, R., 2002. Geological, tectonic and metallogenic relations of South China. University of Tasmania, CODES, Final Report on AMIRA project P603, November, 2002 (132 pp.).