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HIDDEN MINERAL DEPOSITS IN Cu-DOMINATED PORPHYRY-SKARN SYSTEMS: HOW RESOURCE REPORTING CAN OCCLUDE IMPORTANT MINERALIZATION TYPES WITHIN MINING CAMPS

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Abstract

A single mining camp or ore deposit can contain multiple mineral deposit types but may have mineral reserves or resources classified by what a mining or mineral exploration company considers to be the dominant mineralization type in the area. In this paper, we summarize recent work on the challenges of reporting mineral deposits by geologic processes rather than by grades, tonnages, and mineral processing approaches. For example, the Ertsberg-Grasberg district of Indonesia contains several large skarn Cu-Au-Ag deposits, with the discovery outcrop as well as early production entirely in skarn. All early publications and resource descriptions refer to it as the Ertsberg district. Subsequent discovery of the giant Grasberg porphyry Cu-Au-Ag deposit led to the entire district being renamed Grasberg and classified as a porphyry deposit, despite the skarn-focused discovery and early production history of the deposit, as well as the presence of several large skarn deposits within the district. The Ok Tedi Cu-Au-Ag deposit of western Papua New Guinea also is generally thought of as a major porphyry Cu deposit, yet hosts both porphyry and skarn mineralization. Current reserve estimates indicate that the majority of the contained metal within the deposit is hosted by skarns rather than porphyry bodies. Thus, following the Grasberg example in terms of contained metal, Ok Tedi could be classified as a skarn rather than a porphyry deposit. In addition, comparatively minor mineral deposits can prove useful during exploration; this is exemplified by the large Au-Cu-Ag porphyry deposits at Cadia in Australia that were discovered by exploring modest skarn deposits using the Ertsberg-Grasberg skarn-porphyry model. Here, we extend a recent global compilation of economic Cu mineral resources by analyzing cumulative production and reserve-resource data for Ertsberg-Grasberg, Ok Tedi, and Cadia, and provide a brief review of a number of other Cu projects that contain multiple mineralization types. Overall, in order to help inform exploration strategies as well as facilitate the development of more comprehensive and accurate mineral deposit models, there is clearly positive value for the mineral exploration and mining industry in reporting ore reserves and mineral resources by mineralization type.

Introduction

Mineral deposit reporting codes (e.g., JORC, SAMREC, NI 43-101; see Mudd et al., 2013) ensure that a robust approach is used during mineral resource and ore reserve reporting. The main focus of these codes is on grades and tonnages with respect to mineral processing and not allocation by mineralization type, even though, for example, NI 43-101 technical reports must contain a section on deposit types. This can subsequently lead to situations where some mineral deposit types in a camp are overrepresented in terms of resource allocation, whereas others are underrepresented or ignored. Potential confusion over some mineral deposit types, as exemplified by the changing classification of iron oxide copper-gold deposits over the past decade (e.g., Williams et al., 2005; Groves et al., 2010), can also exacerbate the problem. Finally, current mineral resource reporting codes and practices require separation of ore resources that are processed in different ways, but not ore resources that are generated by differing geologic processes (e.g., skarn vs. porphyry).

One example where this misclassification may occur is the porphyry copper environment, where mineral resource reporting generally focuses on "porphyry mineralization" to the exclusion of other potentially cogenetic mineral deposit types that may be within an overarching large "porphyry-related" system. Examples of these potentially hidden mineral deposit types include skarns, epithermal, carbonate-replacement, and sediment-hosted mineralization, and distal vein or manto-type deposits (e.g., Kirkham and Dunne, 1999; Sillitoe, 2010). Although the geological community has recognized the importance of these "hidden" mineral deposit types within larger porphyry systems, with some research splitting porphyry Cu deposits into porphyry, porphyry-related skarn, and associated epithermal classifications (e.g., Kirkham and Dunne, 1999, among others), and other research delineating the differing abundances of rock types and associated mineralization within the porphyry copper environment (e.g., Singer et al., 2008), this is not often the case in the mineral exploration and mining sectors. The combining of grades and tonnages to agglomerate hypogene mineralization together with any skarn, supergene, and/or epithermal mineralization within an individual ore deposit system can lead to the overemphasis of the importance of a single mineral deposit type. Although the complex and often overprinted nature of mineral deposits means that delineation of individual orebody types is difficult and may prevent effective mineral deposit type resource allocation, the delineation of individual orebody types within a mineral resource—for example, separating skarns from other mineralization types—can also lead to

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an increased understanding of the geology of the deposit. This is exemplified by the situation at Cadia in Australia, where examination of modest Cu-Au-Ag skarn ores and deposits led to the identification and delineation of larger, more significant porphyry-type Au-Cu mineralization (Forster et al., 2004; Wood, 2012a, b)—justification in itself for reporting mineral resources by individual mineralization styles and orebody types.

Although the Canadian NI 43-101 code requires a detailed technical report to be published for a given project, including sections on historical work, geologic setting, exploration work, quality control, mineralization style, and reserve/resource estimates, no other current reporting code requires such reports to be made available to the public and investors. Following the lead of NI 43-101 would be a positive step forward on many fronts, not the least of which would be the potential for more substantial studies that assess mineral deposit types—especially the "hidden mineral deposit" types discussed here. Adapting a more detailed approach to mineral resource classification, whereby resources are split, as necessary, into multiple mineral deposit types, could also lead to improvements in the accuracy of quantitative mineral resource assessments and mineral potential modeling (e.g., Singer, 1993; Singer et al., 2005), and allow more robust analysis of production, resource, and reserve statistics in government planning and mineral economics (e.g., Scott and Dimitrakopoulos, 2001).

Here, we present an overview of the problem of comparing code-based mineral resource reporting with more typical economic geology-style subdivision of mineral deposit types using three case studies of mineralization within the Grasberg, Ok Tedi, and Cadia mining districts and information from a select range of other projects. These data highlight the potential for erroneous allocation of in situ and production value to incorrect mineral deposit types, a factor that has significant implications for exploration targeting strategies and assessment of global mineral resources.

Hidden Deposit Case Studies

Although public mineral resource reporting codes and practices allow the precise and accurate assessment of mineral resources and ore reserves within a given mineral deposit or mining camp, these reporting codes still contain a number of potential problems relating to individual mineral deposit type allocations. Here, we focus on three major case studies where a single mineral deposit type has been allocated to often complex mixtures of mineralization styles, with the result being that the allocated mineral deposit type, at best, may not accurately depict the mineralization present within the resource, or, at worst, may not be the dominant mineralization style.

Ertsberg-Grasberg district, Papua, Indonesia

The Ertsberg-Grasberg group of Cu-Au-Ag deposits has been mined continuously since 1972 and represents one of the world's largest Cu-Au-Ag resources. It is located in Papua Province in eastern Indonesia and is majority owned by Freeport-McMoRan Copper & Gold Inc. (aka Freeport), with minority interests owned by Rio Tinto Plc./Ltd. and the Indonesian government. Initial open-cut mining focused on the Ertsberg skarn deposit, with later development of the Gunung Bijih Timur (also known as Ertsberg East) skarn deposit by underground mining. With the discovery of the nearby Grasberg porphyry deposit in 1988, development efforts were quickly shifted to Grasberg, where open-cut mining, along with underground mining in the deeper ore zones, was employed.

The majority of the district resource has been defined by Freeport as porphyry related, even though this resource is known to contain a significant amount of skarn-related ore (e.g., Meinert et al., 1997). The district consists of multiple porphyry, mixed skarn/porphyry, and skarn orebodies, including the Grasberg porphyry deposit, the Ertsberg, Big Gossan, Kucing Liar, Gunung Bijih Timur (Ertsberg East), Dom, and Intermediate ore zone skarn deposits, and the mixed skarn/porphyry Deep ore zone deposit (e.g., Meinert et al., 1997, and others), although this collection of different orebodies sometimes is amalgamated as one single porphyry copper resource (e.g., Cooke et al., 2005). The large Grasberg porphyry deposit also incorporates minor skarn mineralization around the periphery of the intrusion, increasing in importance with depth (MacDonald and Arnold, 1994).

Here, we present a comprehensive data set for production, ore reserves, and resources over time for Ertsberg-Grasberg, and an analysis of the contributions of skarn- and porphyry-related ores to this data set. All data are derived from Freeport and Rio Tinto annual reporting (Freeport-McMoRan Copper & Gold, 1988–2011; Rio Tinto Plc/Ltd, 1995–2011), U.S. Bureau of Mines (1972–1993), Mealey (1996), and Meinert et al. (1997). We arbitrarily assume that the mineralized material reported by Freeport as "Grasberg District Inferred" (based on US SEC requirements) is 100% porphyry mineralization, as no specific description has been published by Freeport; it is likely that this mineralized material includes some skarn mineralization, but, without any detail, it is impossible to state this with any certainty. Given this uncertainty on the classification of this "Grasberg District Inferred" material, and the likelihood that this material contains some skarn-type mineralized material, the porphyry-type Cu discussed here represents the maximum amount of porphyry-type mineralization in the district, with the skarn-type resources discussed here representing a minimum; in other words, it is likely that the values for the Ertsberg-Grasberg district presented here represent an underestimation of the amount of skarn and an overestimation of the amount of porphyry-type mineralization present.

The initial ore reserve for the Ertsberg skarn deposit was 30 Mt at 2.5% Cu, 0.75 g/t Au, and 9 g/t Ag, with ~30 Mt ore mined from 1972 to 1989. Underground mining of the Gunung Bijih Timur skarn deposit began in 1980 and continued to 1993, producing ~60 Mt of ore. The Deep ore zone skarn/porphyry deposit was initially mined by underground mining on a modest scale from 1988 to 1991, producing 2.6 Mt of ore, but this was closed to favor production from the large Grasberg porphyry open cut, which began in 1989. The Intermediate ore zone skarn deposit entered production by underground mining in 1994, extracting ~47 Mt ore by its closure in 2003, while the Deep ore zone mine was restarted in 2000 and has since produced a further 190.2 Mt of ore. Underground mining began on the Big Gossan skarn deposit in 2010, and has produced 0.8 Mt ore to 2011. Cumulative production, reserves, and resources to 2011 are shown in Figures 1 and 2 and Tables 1 and 2.

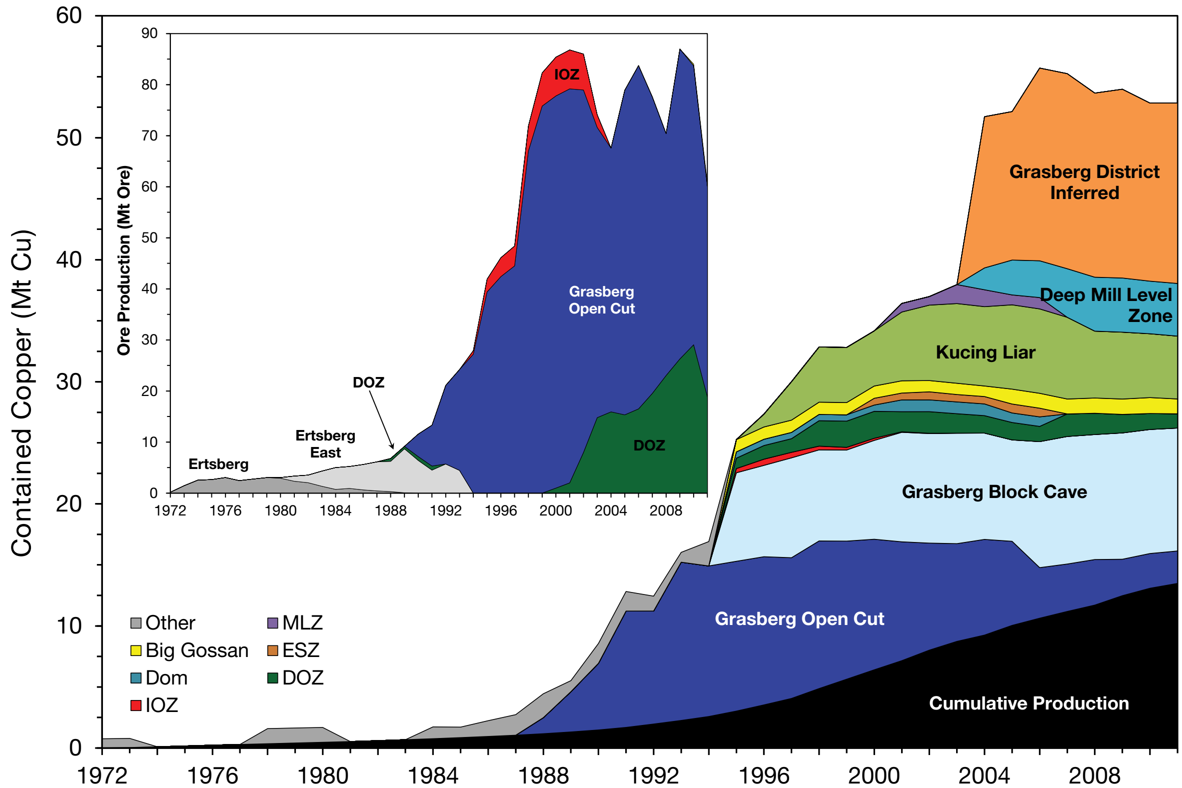

FIG. 1. Grasberg copper production and resources over time, with inset of ore sources by mine. Abbreviations: DOZ = Deep ore zone, ESZ = Ertsberg stockwork zone, IOZ = Intermediate ore zone, MLZ = Mill level zone.

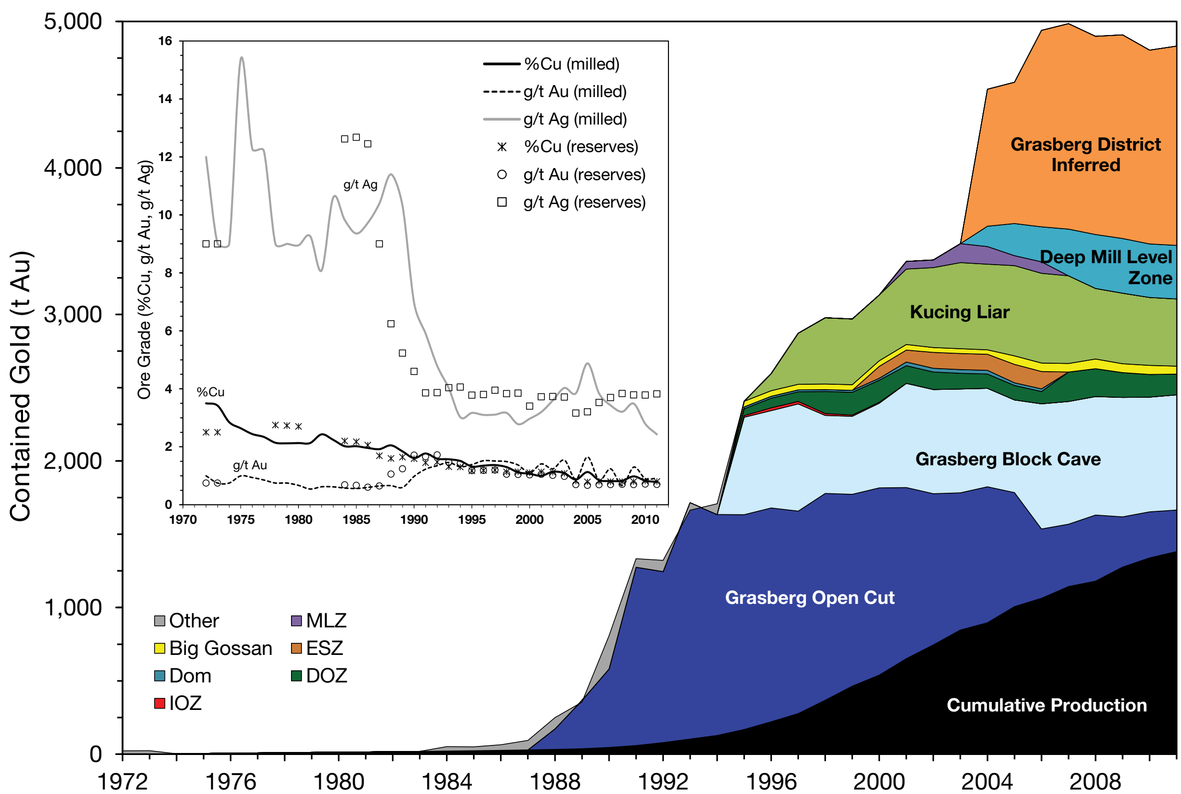

FIG. 2. Grasberg gold production and resources over time, with inset of ore grades by reserves and ore milled. Abbreviations: DOZ = Deep ore zone, ESZ = Ertsberg stockwork zone, IOZ = Intermediate ore zone, MLZ = Mill level zone.

Table 1. Cumulative Production (1972–2011) for the Ertsberg-Grasberg Group

Deposit	Ore type	Mine type	Period	Mt ore	% Cu	g/t Au	g/t Ag	Mt Cu	t Au	t Ag
Ertsberg	Skarn	Open cut	1972–1989	32.6	2.3	0.8	9.1	~0.6*	~22	~188
Gunung Bijih Timur (Ertsberg East)	Skarn	Underground	1980–1993	62.3	2.0	0.7	11.4	~1.03*	~38*	~450*
Intermediate Ore Zone	Skarn	Underground	1994–2003	~47*	~1.1*	~0.45*	~7.7*	~0.45*	~18*	~229*
Big Gossan	Skarn	Underground	2010–2011	0.84	~2.2*	~1*	~13*	~0.02*	~0.7*	~7*
Deep Ore Zone	Skarn/porphyry	Underground	1988–1991; 2000–present	~192.8*	~1*	~0.9*	~5*	~1.5*	~150*	~610*
Grasberg	Porphyry	Open cut	1989–present	~1,070*	~1.1*	~1.3*	~2.8*	~10*	~1,150*	~1,860*
			Total	~1,405*	~1.1*	~1.2*	~3.8*	~13.5	~1,380*	~3,340*

Note: Numbers may not add precisely due to rounding
*Approximate data (i.e., includes some inferred data from graphs; see Mealey, 1996)

Table 2. Combined 2011 Ore Reserves and Mineral Resources for the Ertsberg-Grasberg Group

Deposit	Ore type	Mt ore	% Cu	g/t Au	g/t Ag	Mt Cu	t Au	t Ag
Grasberg (open cut)	Porphyry	312	0.85	0.91	2.18	2.66	283.3	681.4
Grasberg (block cave)	Porphyry	1,019	0.99	0.77	3.35	10.07	786.2	3,409.5
Grasberg district inferred	Porphyry	2,386	0.62	0.57	3.50	14.79	1,360.0	8,351.0
Subtotal	Porphyry	3,717	0.74	0.65	3.35	27.53	2,428.6	12,445
Deep Ore zone	Skarn/porphyry	206	0.57	0.69	2.38	1.17	142.1	490
Subtotal	Skarn/porphyry	206	0.57	0.69	2.38	1.17	142.1	490
Big Gossan	Skarn	56	2.18	0.97	13.45	1.22	54.3	753
Kucing Liar	Skarn	420	1.23	1.09	7.01	5.17	457.8	2,944
Deep Mill Level zone	Skarn	510	0.85	0.72	4.19	4.34	367.2	2,137
Subtotal	Skarn	986	1.09	0.89	5.92	10.72	879.3	5,834
Total		4,909	0.80	0.70	3.82	39.43	3,450	18,769

If all production and reserves-resources from Tables 1 and 2 were classified as porphyry copper mineralization, as is the case in Cooke et al. (2005), this would lead to significant skarn deposits, such as the Big Gossan, Kucing Liar, Deep Mill level zone, and other resources, being misclassified as porphyry mineralization. For the Deep ore zone resource, there are varying classifications applied by different researchers, such as those who argue it is skarn related (Rubin and Kyle, 1997; Coutts et al., 1999; Meinert et al., 2005), while Freeport classifies it as a skarn-porphyry mixed resource (Freeport-McMoRan Copper & Gold, 1988–2011). It is quite likely, therefore, that the total Grasberg skarn resource probably constitutes a major percentage of the total global Grasberg group Cu resource, as shown by individual deposits in Figure 1. Cumulative metal production plus 2011 resource by mineralization type is shown in Table 3, showing the clear significance of skarns at between 20 and 35% of cumulative production and resources.

In comparing the skarn resources of the Grasberg group with those from Mudd et al. (2013), the Ertsberg-Grasberg skarns alone, with 12.86 Mt contained Cu, would rank a clear second in the world, just behind Antamina, with a 2011 resource of 16.06 Mt Cu with 9.93 Mt Zn, plus cumulative production to 2011 of 3.41 Mt Cu and 2.89 Mt Zn.

Ok Tedi, Western Province, Papua New Guinea

The Ok Tedi Cu-Au-Ag deposit of western Papua New Guinea is associated with the 4-km-wide, U-shaped Ok Tedi intrusive complex (Bamford, 1972) and hosts a variety of Cu-Au-Ag mineralization styles within intrusions, skarns, and fractured siltstones centered on two monzonite to monzodiorite stocks that contain disseminated and gold-bearing Cu sulfides (Bamford, 1972; Rush and Seegers, 1990; van Dongen et al., 2010). The majority of mineralization is concentrated within the northernmost Fubilan porphyry and Cu-Au magnetite skarn mineralization surrounding the southern Sydney stock, with leaching and redeposition of Cu forming a Cu-leached but Au-rich cap and an underlying Cu-enriched zone with significant Au (Bamford, 1972; Rush and Seegers, 1990). A number of major mineralized units have been identified at Ok Tedi. These include ore-grade mineralized siltstone adjacent to intrusive rocks and in contact with skarn mineralization, monzodiorites that contain endoskarns and generally sub-ore-grade mineralization, and exoskarns associated with metasomatic alteration of carbonates along the contact with intrusive rocks in the area and monzonites, including the mineralized Fubilan and Southern intrusions that host porphyry-type mineralization (Bamford, 1972; Rush and Seegers,

TABLE 3. Cumulative Metal Production plus 2011 Resources by Mineralization Type for the Ertsberg-Grasberg Group

Ore Type	Mt Cu	t Au	t Ag	Cu (%)	Au (%)	Ag (%)
Skarn	12.86	953.6	6,700	23.84	20.09	30.31
Skarn/porphyry	2.77	291.5	1,100.5	5.13	6.14	4.98
Porphyry	38.32	3,500.5	14,307	71.03	73.76	64.72
Total	53.95	4,745.6	22,107.5			

1990; Hendry et al., 2005). The exoskarns at Ok Tedi contain generally higher grades of mineralization than the associated intrusive rocks, and have undergone variable oxidation, which produced zones of significantly elevated abundances of acid-soluble Cu (Hendry et al., 2005).

The initial ore reserves at start of production in 1984 were 414.7 Mt at 0.76% Cu and 0.76 g/t Au, with a small amount of skarn ore (28.9 Mt at 1.25% Cu and 1.58 g/t Au in 1988; Rush and Seegers, 1990). Total production to 2011 was ~645.7 Mt at ~0.79% Cu, ~0.89 g/t Au, and ~2.1 g/t Ag, with 4.22 Mt Cu, 403.9 t Au, and ~815 t Ag extracted (data compiled from Broken Hill Proprietary Company Ltd, 1984–2000; England et al., 1991; Gigmai et al., 1991; Baumgardt, 2006; GRID-Arendal, 2011). Although the 1988 ore reserves contained only a small amount of skarn mineralization, the 2004 mineral resource estimate included measured and indicated resources of 543 Mt at 0.77% Cu and 0.93 g/t Au, with all skarn types (sulfide, pyrite, endo- and oxidized skarns) containing 47.1% of the remaining reserve tonnage, but a total of 71.4% and 75.1% of the remaining Cu and Au, respectively, constituting the most important single component of the delineated mineralization (see Table 4; Hendry et al., 2005). In comparison, porphyry-type mineralization within monzonites in the deposit contains some 38% of the reserve tonnage, but only 22% and 10% of the contained Cu and Au, respectively (Hendry et al., 2005). This indicates that the majority of the contained metal within Ok Tedi is hosted by skarn mineralization, suggesting that instead of being considered a giant porphyry deposit, it should now, in fact, be considered a giant skarn deposit.

Cadia Valley Group, New South Wales, Australia

The Cadia Valley Group of Au-Cu-Ag mines is one of Australia's largest such resources and is owned by Newcrest Mining. Although intermittent but very small scale copper mining occurred in the Cadia area from the mid-1800s onward, modern exploration began in the 1960s and initially focused on the Big Cadia prospect, with the smaller Little Cadia skarn resource some 2.5 km to the east (Forster et al., 2004). In 1970, Big Cadia was estimated to host 15 Mt at 0.81% Cu with Au-Ag credits, increasing to 30 Mt ore at 0.49% Cu, 0.4 g/t Au, and 4 g/t Ag in 1976; in comparison, Little Cadia was estimated to host ~8 Mt of ore at 0.49% Cu, 0.4 g/t Au, and 4 g/t Ag in 1976 (Malone, 2011).

TABLE 4. Proportion of Mineralization Types at Ok Tedi, ~2004 (adapted from Hendry et al., 2005)

Lithology		% ore tonnage	% total Cu	% total Au
Siltstone		0.5	0.4	0.3
Monzodiorite	Porphyry	14.6	6.3	7.2
Monzonite		37.8	21.8	17.5
Endoskarn	Skarn	12.6	13.3	13.5
Pyrite skarn		9.2	13.6	21.0
Sulfide skarn		24.7	44.0	39.8
Oxidized skarn		0.6	0.5	0.8
Total	100.0	100	100	

In the 1980s, geologists explored the area around the Big Cadia skarn deposit and, by using the Ertsberg-Grasberg porphyry-skarn complex as a model and skarn mineralization to identify fluid dynamic regimes and as a vector toward other mineralization, discovered the Cadia Hill porphyry Au-Cu-Ag resource in 1992 (Forster et al., 2004; Wood, 2012a, b). Further exploration led to the discovery of the Cadia East porphyry Au-Cu deposit in 1994 and the deeper Ridgeway porphyry Au-Cu deposit in 1996 (Forster et al., 2004; Wood, 2012a, b). Cadia Hill began production in 1998 as an open-cut mine and flotation mill, with underground mining at Ridgeway commencing in early 2000 and at Cadia East in late 2010. Cumulative production and reserves-resources to 2011 are shown in Figure 3 and Tables 5 and 6. Based on reported Au-Cu-Ag prices, the revenue averages ~64% from gold, ~34% from copper, and ~2% from silver, with all production, price, and resource data presented here from Newcrest Mining annual reports (Newcrest Mining Ltd, 1991–2011), Moorhead et al. (2001), and Malone (2011).

Although the size and grade of the skarn mineralization within the Cadia Valley Group are both significantly less than that within the Ertsberg-Grasberg Group, the discovery of the porphyry Au-Cu deposits at Cadia may not have occurred if the skarn mineralization in this area, namely the Big and Little Cadia deposits and various Fe skarns, had not been discovered and exploited for more than a century (e.g., Wood, 2012a).

Other examples

A variety of examples of the conflict in reporting total mineral resources versus individual deposits by mineralization type exist, and here we simply highlight a few. A detailed compilation of reserves-resources and available cumulative production data of the three case study projects plus additional projects discussed briefly below is given in Table 7.

Gaspé, Canada: The Gaspé Cu-Ag-Mo-Au project in Quebec, Canada, included porphyry and skarn deposits, and operated almost continuously from 1955 to 1999 (data from Natural Resources Canada, 1944–2009). The project included skarn ores at Needle Mountain and Needle East and porphyry ores at Copper Mountain. As can be seen from Table 7, the proportion of skarn ores from 1974 reserves was about 20.3% of the total, although the project did not report production separately from each deposit.

Bingham Canyon, USA: The Bingham Canyon project is widely regarded as a classic porphyry Cu-Au-Mo-Ag deposit associated with significant skarn mineralization (e.g., Atkinson and Einaudi, 1978; Sillitoe, 2010, and references therein) and has been almost continuously operating since 1906, with some small-scale Pb-Zn-Ag and Cu mining occurring in the late 1800s. In the immediate vicinity of the main porphyry

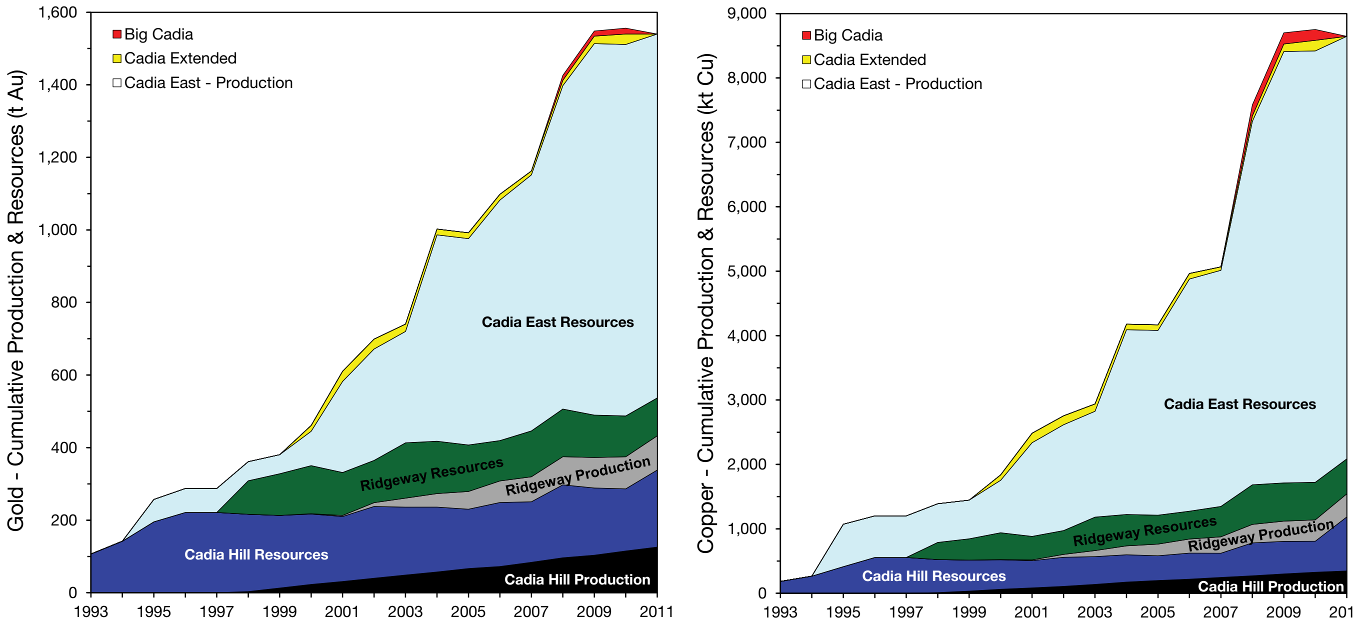

FIG. 3. Cadia Valley gold (left) and copper (right) production and resources over time.

resource, a variety of skarn, vein, replacement, and manto deposits have already been mined with varying degrees of success (e.g., the unsuccessful Carr Fork deposit, 1978–1981, and late-1800s ventures; Tooker, 1990), with a small but high-grade skarn deposit (the North Rim skarn) being reported separately from porphyry-dominated resources and reserves for the first time in 2011 (Table 7). However, insufficient historical production data is available to ascertain the proportion of skarn ores in all mining at Bingham to date.

Buenaventura del Cobre (formerly Cananea), Mexico: The Buenaventura del Cobre Cu project, formerly Cananea and currently owned by Grupo Mexico, contains a variety of mineralization types, including skarn, breccia pipes, and vein-type ores (Meinert, 1982). According to Meinert (1982), by

TABLE 5. Cumulative Production (1998–2011) for the Cadia Valley Group

Deposit	Mine type	Period	Mt ore	% Cu	g/t Au	kt Cu	t Au	t Ag	t WR
Cadia Hill	Open cut	1998–2011	221.1	0.18	0.75	346.8	125.76	»20	489.1
Ridgeway	Underground	1980–1993	54.74	0.73	2.04	357.6	94.26	nd	nd
Cadia East	Underground	1994–2003	0.338	0.20	0.68	0.6	0.18	nd	nd
Porphyry-related		Total	276.2	0.29	1.00	704.9	220.2	»20	»490

Note: nd = no data; WR = waste rock; silver production included in Cadia Hill (data only available for 2011)

TABLE 6. 2011 Ore Reserves and Mineral Resources for the Cadia Valley Group

Deposit	Ore type	Mt ore	g/t Au	% Cu	g/t Ag	kt Cu	t Au
Other[1]	Porphyry	560	0.38	0.15	nd	838.0	212.4
Ridgeway/Ridgeway Deeps	Porphyry	148.1	0.71	0.37		543.6	104.4
Cadia East	Porphyry	2,300	0.44	0.29		6,560	1,003.0
Total		3,008.1	0.44	0.26	0.49	7,942	1,319.8
Little Cadia[2]	Skarn	8[2]	0.38[2]	0.49[2]		32[2]	3.0[2]
Big Cadia (2010 data)	Skarn	42.3	0.38	0.40		169	16.1
Cadia Hill (2010 data)	Porphyry	408	0.42	0.12		482	171.4
Cadia Extended (2010 data)	Porphyry	82.3	0.35	0.20		165	28.8

[1] For 2011, Newcrest reported only Ridgeway, Cadia East, and "Other," with the latter including all resources such as Cadia Hill, Cadia Extended, and Big Cadia; some 2010 data shown for comparison

[2] Little Cadia resource from Forster et al. (2004), although it should be noted that Newcrest has never formally included Little Cadia in its annual mineral resource reporting

TABLE 7. Comparison of 2011 Ore Reserves and Mineral Resources by Mineralization Type and Available Cumulative Production

		Total ore reserve & mineral resource						Cumulative production								Type split	
Mine	Deposit type	Mt ore	% Cu	g/t Au	Mt Cu	t Au	Other	Mt ore	% Cu	g/t Au	Mt Cu	t Au	Other	Mt WR	Years	Cu (%)	Au (%)
Grasberg Group	Porphyry	3,717	0.74	0.65	27.53	2,429	12,445 t Ag	~1,070	~1.1	~1.3	~10	~1,150	~1,860 t Ag	~3,820	1972–2011	73.7%	83.4%
	Skarn/porphyry	206	0.57	0.69	1.17	142	490 t Ag	~192.8	~1	~0.9	~1.5	~150	~610 t Ag	nd		11.1%	10.9%
	Skarn	986	1.08	0.89	10.72	879	5,834 t Ag	~142.7	~1.8	~0.64	~2.1	~79	~874 t Ag	nd		15.2%	5.7%
	Total	4,909	0.80	0.70	39.43	3,450	18,769 t Ag	~1,405	~1.1	~1.2	~13.5	~1,379	~3,344 t Ag	~3,820		nd	nd
Buenavista del Cobre	Total	5,256.1	0.43	nd	20.55	nd	3.1 g/t Ag	420.81	0.38	nd	0.963	nd		288.5	2003–2011	nd	nd
Cadia Group (2010 resource data)	Porphyry	2,992.3	0.26	0.45	7.93	1,337	Ag	276.2	0.29	1.00	0.705	220.2	Ag	489.1	1998–2011	97.5%	98.6%
	Skarn[g]	50.3	0.40	0.37	0.20	18.5		0	0	0	0	0				2.5%	1.4%
Tintaya	Skarn	88	1.17	0.18	1.03	15.8	Nd	86.76	1.47	?	1.39	17.0	Ag	861.11	1996–2011	100	100
Antamina	Skarn	1,914	0.84	nd	16.06	nd	0.54% Zn, Ag, Mo	320.62	1.22	nd	3.41	nd	Ag, Pb, Zn, Mo	941.10	2001–2011	100	100
Gaspé (1974 resource data)	Porphyry	289	0.41	nd	1.18	nd	nd	nd	nd	nd	nd	»0.5	»127 t Ag	nd	1955–1999	61.6%	nd
	Skarn	61.5	1.20		0.75			nd	nd		nd					38.4%	
	Total	350.5	0.55		1.92			144.66	0.78		1.13					nd	
Ok Tedi (1988 skarn/2009 total resource data)	Skarn	28.9	1.25	1.58	0.36	nd	Ag	nd	nd	nd	nd	nd	~815 t Ag	nd	1984–2011	see text	see text
	Total	353	0.58	0.77	2.05	271.8		~646	0.79	0.89	4.22	403.9		~968.3			
Ely (Robinson)[1]	Total	899.9	0.35	0.15	3.13	135.4	Ag, Mo	99.67	0.58	0.32	0.403	19.1	Ag, Mo	~392	2004–2011	nd	nd
Bingham Canyon	Porphyry	939	0.45	0.19	4.18	180.6	Ag, Mo	nd	nd	nd	nd	nd	Ag, Mo	1,496.5	1996–2011	85.1%	84.8%
	Skarn	20	3.65	1.62	0.73	32.4		nd	nd	nd	nd	nd				14.9%	15.2%
	Total	959	0.51	0.22	4.91	213.0		803.85	0.59	0.40	4.28	224.5				nd	nd
Las Bambas[2]	Skarn (2007)	429	1.17	0.12	5.02	51.5	Ag, Mo	nd	nd	nd	nd	nd	nd	nd	nd	74.0%	89.3%
	Total (2007)	721	0.94	0.08	6.78	57.7										nd	nd
	Skarn/other (2011)	1,710	0.62	0.05	10.53	80.4										nd	nd

Notes: nd = no data, WR = waste rock; sources for some data discussed in main text

[1]Some 20% of the Cu mineralization in the Ely (Robinson) deposit is skarn related, according to Laznicka (2010), although no more robustly assessed figures are available

[2]2007 resource from Xstrata Plc. media release, March 6, 2007; 2011 resource from Xstrata 2011 annual report

August 1979, production was ~152 kt Cu from skarn sources, 762 kt Cu from breccia pipe mineralization, and some 1,354 kt Cu from the disseminated supergene and primary breccia pipe mineralization (i.e., total of 2.268 Mt Cu), with reserves in disseminated supergene and primary breccia pipes of 12.93 Mt Cu and a further 181 kt Cu in breccia-skarn ores. The 2011 total mineral resource contains 20.55 Mt Cu (see Table 7), but no distinction is made by mineralization types.

Las Bambas, Peru: The Las Bambas Cu-Mo-Au project consists of three deposits in the Tintaya district of Peru, namely Sulfobamba, Chalcobamba, and Ferrobamba, all of which are associated with the Ferrobamba Formation, a regionally important limestone that hosts significant skarn mineralization, with these deposits being dominated by skarn ore but also including small amounts of porphyry or other types of ore (e.g., Perello et al., 2003; Maher, 2010). Xstrata, the owner of the project, reported resources by deposit and ore type in 2007, but in 2011 they only reported total resources; data for both are provided in Table 7. Based on the 2007 resource estimate, skarn ore represents about 59.5% of ore but 74.1% and 89.3% of the total contained Cu and Au, respectively, while Mo is similarly distributed.

Summary and Conclusions

Here, we have presented a number of case studies that exemplify the importance of understanding mineral deposit types and subdividing global mineral resources into individual, genetically constrained styles or types of mineralization, focusing on porphyry Cu deposits and other associated mineralization types. In these deposits, agglomeration of different types of mineral resources and ore reserves (e.g., skarn, supergene, and/or epithermal mineralization) as a single mineral deposit-type orebody can lead to the overemphasis of the importance of this mineral deposit type. This misclassification or underclassification may lead to the overrepresentation of given mineral deposit types in a camp in terms of resource allocation and total in situ and production value, with other mineral deposit types being underrepresented or ignored. In comparison, splitting a global resource by individual mineral deposit types can increase understanding of mineralizing processes and the geology of a mining district; the importance of this increased understanding is shown clearly in the Cadia district of Australia, where modest Cu-Au-Ag skarn mineralization enabled the discovery of larger porphyry-style mineralization. The importance of subdivision is also clear in the Grasberg and Ok Tedi mining camps, both of which contain world-class porphyry and skarn mineralization. At the Ertsberg-Grasberg district, although the majority of the resource is porphyry related, skarn-related mineralization accounts for some 20 to 35% of cumulative Cu-Au-Ag production and remaining resources. A similar situation exists at Ok Tedi, where Cu-Au-Ag mineralization is predominantly hosted by porphyritic intrusives and skarns. Although initial reserves at Ok Tedi contained only a minimal amount of skarn mineralization, the 2004 resource estimate allocated 71.4% and 75.1% of the remaining Cu and Au to skarn-type mineralization, making skarn orebodies the most important single component of the remaining mineralization. Other examples where skarn mineralization has significantly contributed but not necessarily been given the recognition it deserved are Gaspé in Quebec, Canada, Buenaventura del Cobre in Mexico, and the Las Bambas Cu-Mo-Au project in Peru. These case studies highlight the potential for erroneous allocation of in situ and production value to incorrect mineral deposit types, a factor that has significant implications for exploration targeting strategies and assessment of global mineral resources. Both improved mineral deposit type classification and an increase in awareness in the mining industry of the importance of potentially neglected mineralization styles in mining camps and individual orebodies could have a significantly positive impact on the mineral exploration and mining industry. Given this, we recommend that the economic geology community include tables showing resources and reserves separated by deposit type in articles describing mining districts and deposits, and that industry move more toward NI 43-101 styles of reporting that include, at the least, a discussion of mineral deposit types; these approaches can allow both academia and industry to build up a more complete picture of the relative importance of differing mineral deposit types.

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REFERENCES

Atkinson, Jr., W.W., and Einaudi, M.T., 1978, Skarn formation and mineralization in the contact aureole at Carr Fork, Bingham, Utah: ECONOMIC GEOLOGY, v. 73, p. 1326–1365.

Bamford, R.W., 1972, The Mount Fubilan (Ok Tedi) porphyry copper deposit, Territory of Papua and New Guinea: ECONOMIC GEOLOGY, v. 67, p. 1019–1033.

Baumgardt, K., 2006, The Ok Tedi pages: Ecological and social impact of large mining projects on a developing country, *in* von Gleich, A., Ayres, R.U., and Gößling-Reisemann, S., eds., Sustainable metals management: Securing our future—steps towards a closed loop economy: Dordrecht, Netherlands, Springer, p. 483–515.

Broken Hill Proprietary Company Ltd (BHP), 1984–2000, various: Melbourne, Australia, Broken Hill Proprietary Company Ltd.

Cooke, D.R., Hollings, P., and Walshe, J.L., 2005, Giant porphyry deposits: Characteristics, distribution, and tectonic controls: ECONOMIC GEOLOGY, v. 100, p. 801–818.

Coutts, B.P., Susanto, H., Belluz, N., Flint, D., and Edwards, A., 1999, Geology of the deep ore zone, Ertsberg East skarn system, Irian Jaya: Pacrim '99 Congress, Bali, Indonesia, 1999, Proceedings: Melbourne, Australasian Institute of Mining and Metallurgy, p. 539–547.

England, J.K., Kilgour, I., and Kanau, J.L., 1991, Processing copper-gold ore at Ok Tedi: Australasian Institute of Mining and Metallurgy, PNG Geology, Exploration and Mining Conference, Rabaul, Papua New Guinea, 1991, Proceedings, p. 183–190.

Forster, D.B., Seccombe, P.K., and Phillips, D., 2004, Controls on skarn mineralization and alteration at the Cadia deposits, New South Wales, Australia: ECONOMIC GEOLOGY, v. 99, p. 761–788.

Freeport-McMoRan Copper & Gold (FMCG), 1988–2011, Form 10-K reports: Phoenix, USA, Freeport-McMoRan Copper & Gold.

Gigmai, W., Kepa, J., Pai, E., and Zwaan, J., 1991, Aspects of mining at Ok Tedi: Australasian Institute of Mining and Metallurgy, PNG Geology, Exploration and Mining Conference, Rabaul, Papua New Guinea, 1991, Proceedings, p. 175–182.

GRID-Arendal, 2011, Waste from consumption and production—the Ok Tedi case: A pot of gold: Norway, GRID-Arendal Centre, United Nations Environment Programme (UNEP), available online at www.grida.no/publications/vg/waste/page/2859.aspx.

Groves, D.I., Bierlein, F.P., Meinert, L.D., and Hitzman, M.W., 2010, Iron oxide copper-gold (IOCG) deposits through Earth history: Implications for origin, lithospheric setting, and distinction from other epigenetic iron oxide deposits: ECONOMIC GEOLOGY, v. 105, p. 641–654.

Hendry, J.W, Evans, L., and Wiatzka, G., 2005, Technical report on the Ok Tedi Mining Limited Mt. Fubilan copper-gold mine mineral resource and mineral reserve estimates, Papua New Guinea: Toronto/Vancouver, Canada, Roscoe Postle Associates Inc. for Inmet Mining Corporation, 155 p.

Kirkham, R.V., and Dunne, K.P.E., 1999, World distribution of porphyry, porphyry-associated skarn, and bulk-tonnage epithermal deposits and occurrences: Geological Survey of Canada Open File 3792a, 87 p.

Laznicka, P., 2010, Giant metallic deposits: Future sources of industrial metals, 2nd edition: Heidelberg, Germany, Springer, 950 p.

MacDonald, G.D., and Arnold, L.C., 1994, Geological and geochemical zoning of the Grasberg igneous complex, Irian Jaya, Indonesia: Journal of Geochemical Exploration, v. 50, p. 143–178.

Maher, K.C., 2010, Skarn alteration and mineralization at Coroccohuayco, Tintaya district, Peru: ECONOMIC GEOLOGY, v. 105, p. 263–283.

Malone, E., 2011, The Cadia Valley mines—a mining success story: Melbourne, Australia, Australasian Institute of Mining & Metallurgy, Spectrum no. 19, 264 p.

Mealey, G.A., 1996, Grasberg: Mining the richest and most remote deposit of copper and gold in the world, in the mountains of Irian Jaya, Indonesia: New Orleans, USA, Freeport-McMoRan Copper & Gold, 384 p.

Meinert, L.D., 1982, Skarn, manto, and breccia pipe formation in sedimentary rocks of the Cananea mining district, Sonora, Mexico: ECONOMIC GEOLOGY, v. 77, p. 919–949.

Meinert, L.D., Hefton, K.K., Mayes, D., and Tasiran, I., 1997, Geology, zonation, and fluid evolution of the Big Gossan Cu-Au skarn deposit, Ertsberg district, Irian Jaya: ECONOMIC GEOLOGY, v. 92, p. 509–526.

Meinert, L.D., Dipple, G.M., and Nicolescu, S., 2005, World skarn deposits: ECONOMIC GEOLOGY 100TH ANNIVERSARY VOLUME, p. 299–336.

Moorhead, C.F., Dunham, P.B., Eastwood, G.J., and Leckie, J.F., 2001, Cadia Hill: From discovery to a measured resource—A case study: Parkville, Victoria, Australia, Australasian Institute of Mining & Metallurgy Monograph 23, p. 97–108.

Mudd, G.M., Weng, Z., and Jowitt, S.M., 2013, A detailed assessment of global Cu resource trends and endowments: ECONOMIC GEOLOGY, v. 108, p. 1163–1183.

Newcrest Mining Ltd, 1991–2011, Annual reports: Melbourne, Australia, Newcrest Mining Ltd.

Natural Resources Canada, 1944–2009, Canadian Minerals Yearbook: Ottawa, Ontario, Canada, Mining Sector, Natural Resources Canada.

Perello, J., Carlotto, V., Zarate, A., Ramos, P., Posso, H., Neyra, C., Caballero, A., Fuster, N., and Muhr, R., 2003, Porphyry-style alteration and mineralization of the middle Eocene to early Oligocene Andahuaylas-Yauri belt, Cuzco Region, Peru: ECONOMIC GEOLOGY, v. 98, p. 1575–1605.

Rio Tinto Plc/Ltd, 1995–2011, Annual reports: Melbourne, Australia/London, UK.

Rubin, J.N., and Kyle, J.R., 1997, Precious metal mineralogy in porphyry-, skarn-, and replacement-type ore deposits of the Ertsberg (Gunung Bijih) district, Irian Jaya, Indonesia: ECONOMIC GEOLOGY, v. 92, p. 535–550.

Rush, P.M., and Seegers, H.J., 1990, Ok Tedi copper-gold deposits: Carlton, Victoria, Australia, Australasian Institute of Mining & Metallurgy Monograph 14, p. 1747–1754.

Scott, M., and Dimitrakopoulos, R., 2001, Quantitative analysis of mineral resources for strategic planning: Implications for Australian Geological Surveys: Natural Resources Research, v. 10, p. 159–177.

Sillitoe, R.H., 2010, Porphyry copper systems: ECONOMIC GEOLOGY, v. 105, p. 3–41.

Singer, D.A., 1993, Basic concepts in three-part quantitative assessments of undiscovered mineral resources: Nonrenewable Resources, v. 2, p. 69–81.

Singer, D.A., Berger, V.I., Menzie, W.D., and Berger B.R., 2005, Porphyry copper deposit density: ECONOMIC GEOLOGY, v. 100, p. 491–514.

Singer, D.A., Berger, V.I., and Moring, B.C., 2008, Porphyry copper deposits of the world—Database and grade and tonnage models, 2008: U.S. Geological Survey Open-File Report 2008–1155, 45 p.

Tooker, E.W., 1990, Gold in the Bingham district, Utah: U.S. Geological Survey Bulletin 1857-E, p. 1–16.

U.S. Bureau of Mines, 1972–1993, Minerals yearbook: USA, U.S. Bureau of Mines.

van Dongen, M., Weinberg, R.F., Tomkins, A.G., Armstrong, R.A., and Woodhead, J.D., 2010, Recycling of Proterozoic crust in Pleistocene juvenile magma and rapid formation of the Ok Tedi porphyry Cu-Au deposit, Papua New Guinea: Lithos, v. 114, p. 282–292.

Williams, P.J., Barton, M.D., Johnson, D.A., Fontboté, L., de Haller, A., Mark, G., Oliver, N.H.S., and Marschik, R., 2005, Iron oxide copper-gold deposits: Geology, space-time distribution, and possible modes of origin: ECONOMIC GEOLOGY 100TH ANNIVERSARY VOLUME, p. 371–405.

Wood, D., 2012a, Discovery of the Cadia Deposits, NSW, Australia (Part 1): Society of Economic Geologists Newsletter 88, p. 1–18.

——2012b, Discovery of the Cadia Deposits, NSW, Australia (Part 2): Society of Economic Geologists Newsletter 89, p. 1–22.