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A Detailed Assessment of Global Cu Resource Trends and Endowments*

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Abstract

Copper plays a crucial role in modern society across the world, contributing to infrastructure, technology, and lifestyles. Although mineral resources are commonly considered to be "finite," global Cu production has grown steadily throughout the 20th century, and has been matched by substantial growth in estimated Cu reserves and resources. While there is growing concern about "peak oil," there is very little research about "peak minerals." In this paper, we present a detailed compilation and assessment of globally reported Cu resources by project and standard deposit types for the year 2010. The minimum amount of Cu reported globally as mineral resources is 1,780.9 Mt Cu, split over a total of 730 projects, with a further 80.4 Mt Cu in China. In addition, our compiled data indicate that global Cu resources continue to increase, despite a coincident increase in Cu production over time, along with declining cutoff and ore grades, increasing awareness of environmental issues, and other related aspects. Our data compilation indicates that the vast majority of global copper resources are hosted by Cu porphyry deposits, especially in Chile, with Cu porphyry deposits containing some 10 times more Cu than any other mineral deposit type. Overall, there are abundant Cu resources already identified that can meet growing global demands for some decades to come; the primary factors that govern whether a given project is developed will be social, economic, and environmental in nature.

Introduction

Mineral resources have a key global role in modern technology, infrastructure, and increasing improvements in lifestyles. It is commonly held that mineral resources are finite and that mining is therefore an unsustainable activity by its very nature (e.g., Mudd, 2010a; Amezaga et al., 2011). The paradox, however, is that although global minerals and metals production continues to grow strongly to meet demand, most remaining mineral resources also continue to grow and are often reported to be sufficient for at least a few decades or more (Wellmer and Becker-Platen, 2000; International Institute for Environment and Development, and World Business Council for Sustainable Development, 2002). This has been a prominent pattern of mining throughout the 20th century, due in large part to low cost and reliable energy inputs, new mining and processing technologies, growing demand, and exploration success (Doggett, 2000; International Institute for Environment and Development, and World Business Council for Sustainable Development, 2002; Mudd, 2010a). An open question remains, however, as to how long this historical pattern can continue, given that, at least conceptually, mineral resources are "finite."

In the 1950s, petroleum geologist M. King Hubbert first applied the concept of a "peak" model to annual oil production—as finite oil resources are discovered and developed, there must be a gradual rise and then inevitable decline in production (Hubbert, 1956). While the problem of peak oil is now more widely recognized and debated (e.g., Bentley, 2002; Feng et al., 2008; Sorrell et al., 2009; Smith, 2012), there is minimal research about the extent to which other minerals and metals may or may not meet the "peak X" concept (e.g., Prior et al., 2011; Arndt and Ganino, 2012), though some try to refute it (e.g., Rustad, 2012). Whereas oil reservoirs are typically large geologic structures, mineral and metal deposits are often small features hidden in regional geologic complexity. This leads to the problem that it takes considerable effort to find a mineral deposit and demonstrate it as economic and worth mining. To minimize exploration and development costs, it is common practice in the mining industry not to drill an orebody out entirely, but to delineate an extractable reserve using a minimal amount of drilling, with subsequent conversion of resources to mineable reserves during the lifetime of a mine. Over time, ongoing greenfield and brownfield exploration can continue to locate new deposits or expand resources at operating mines, changing market conditions can make a project profitable (or otherwise), or new technology can enable development of previously uneconomic projects.

The most widely cited group that regularly estimates global mineral resources is the United States Geological Survey (USGS), which publishes approximate estimates of numerous metals and minerals in its annual *Mineral Commodity Summaries* (e.g., USGS, 1996–2011). The USGS adopts a strict system of classification for mineral deposits, based on the McKelvey system (see USGS, 1996–2011), whereby economic projects are listed as "reserves," and subeconomic and more marginal projects are added to reserves to form the "reserves base." The reserves include the recoverable amount of copper from operating mines and projects under development, whereas the reserves base includes reserves plus additional mineral resources reported at explored and developing projects, although it should be noted that the USGS stopped reporting reserves base starting in 2009. The USGS estimates of reserves base for 2008 and reserves for 2010 and 2011 by country for copper are shown in Table 1, including equivalent national estimates.

It is a common misconception that USGS-reported reserves are an absolute (or, perhaps, "finite") amount and,

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Table 1. USGS Reserves (2010, 2011) and Reserves Base (2008) for Copper (Mt), Including Respective National Resource Estimates

Country	Reserves (2010)	Reserves (2011)	Reserves base (2008)	National estimate
Chile	150	190	360	
United States	35	35	70	70
Peru	90	90	120	
Australia	80	86	43	131.6
China	30	30	63	80.41
Mexico	38	38	40	
Indonesia	30	28	38	
Canada	8	7	20	7.29
Zambia	20	20	35	
Russia	30	30	30	
Kazakhstan	18	7	22	
Poland	26	26	48	
South Africa				13
India				11.42
Congo (Kinshasa)		20		
Other	80	80	110	
Total[1]	630	690	1,000	

Notes: National resource estimates from Australia (Geoscience Australia, 2012), Canada (Natural Resources Canada, 2010), China (Hongtao et al., 2011), India (Indian Bureau of Mines, 1958–2010), South Africa (Chamber of Mines of South Africa, 2011)

[1] Totals rounded down to two significant figures

hence, there are regular claims that the world is running out of mineral resources. For example, Cohen (2007) claimed copper reserves would only last 38 years considering the global consumption rates at the time, whereas, more recently, the British Broadcasting Corporation (BBC) featured a similar article claiming copper reserves would last just 32 years (BBC, 2012). The critical caveats applied in both cases were that new discoveries and technologies were excluded, while consumption was either considered to be constant or allowed to increase at historical rates.

As noted previously, companies will only invest the minimal effort required to demonstrate an ore reserve for a profitable project and, hence, formal estimates of reserves alone will exclude additional mineral resources that are known but not quantified in as much detail as ore reserves. Thus, there is a need for research that examines long-term trends in recoverable minerals, and this should be based on total mineral resources. In this way, it should become clear that there are indeed substantial resources well within the reach of present technology and economics and that other factors, especially social and environmental issues, will govern the future of mining, rather than simply "x years left."

In this paper, we present a detailed analysis of reported global copper mineral resources in order to underpin future scenarios for copper mining as well as provide fundamental evidence on the key trends in copper resources and whether the concept of "peak copper" is realistic. The paper contains an extensive resource database, compiled almost exclusively from company reporting for 2010, with all resources being classified using standard deposit types. The paper will prove useful and valuable for all concerned with the future of the copper mining sector and related environmental, social, and economic issues.

Mineral Resource Accounting

Copper deposit types

A wide range of mineral deposit types host significant copper resources and reserves; a concise description of various important deposit types is provided in the Appendix. Where a single project contains ore formed as a result of overlapping mineral deposit types, the deposit has, if possible, been classified by the dominant provenance, i.e., the process that produced the majority of ore. For example, although Grasberg contains both porphyry Cu- and skarn-derived mineralization, the majority of the resource is porphyry related (Jowitt et al., 2013) and, therefore, Grasberg has been classified as a porphyry deposit. This was not possible in some cases, where resources and/or reserves were not reported by mineral deposit type; in these cases, namely 22 out of the 730 individual projects in our database, a mixed mineral deposit type has been assigned. Finally, in the rare cases where a mineral deposit type has not been assigned to a resource or has not been disclosed by the mining or exploration company, a classification has been assigned based on the geologic information available.

Mineral resource accounting

In order to define a mineral deposit as economic, a range of detailed technical studies need to be undertaken, such as close-spaced drilling, metallurgical testing, mine design and planning, environmental, social, and economic studies, and so on. If a deposit meets the relevant criteria, it can then be classified accordingly and, potentially, mined.

Given the complexity of justifying a mineral deposit as profitable and the need to provide clear justification and communication of such results to the public and investors (as most mining companies are publicly listed on their respective national stock exchange), the global mining industry uses formal codes for assessing and reporting mineral resources. In general, all mining companies listed on a stock exchange are required to use their national code. In Australia, companies use the Joint Ore Reserves Committee (JORC) Code (Stephenson, 2001; Australasian Institute of Mining and Metallurgy et al., 2004), whereas Canada has National Instrument 43-101 (NI 43-101; Ontario Securities Commission, 2011), South Africa has the South African Mineral Resource Committee Code (SAMREC; South African Mineral Resource Committee Working Group, 2009), and other codes are used in other countries or regions (e.g., Russia, China, Europe, the United States). A global committee was established in 1994 called the Committee for Mineral Reserves International Reporting Standards (and known as CRIRSCO), under the auspices of the Council of Mining and Metallurgical Institutes, to provide for international cooperation on reserve-resource reporting codes. The member regions or countries of CRIRSCO include Australasia, Canada, Chile, Europe, South Africa, and the United States.

The two primary aspects that all statutory codes consider are geologic and economic probability in claiming a mineral resource as profitable. A range of important "modifying factors" are compulsory to consider, such as mining, metallurgical, economic, marketing, legal, environmental, social, and governmental factors. There are two primary categories used to classify a mineral deposit—ore reserves and mineral resources.

The typical distinction is that ore reserves have a very high economic and geologic probability of profitable extraction, whereas mineral resources have a reasonable geologic probability of extraction but are less certain to be economic. Common definitions are as follows:

1. Ore reserves: For ore reserves, assessments demonstrate at the time of reporting that profitable extraction could reasonably be justified. Ore reserves are subdivided, in order of increasing confidence, into probable ore reserves and proven ore reserves.
2. Mineral Resources: For mineral resources, the known location, quantity, grade, geologic characteristics, and continuity of a mineral resource indicate that there are reasonable prospects for eventual economic extraction, although not all modifying factors have been assessed and, hence, some uncertainty remains. Mineral resources are subdivided, in order of increasing geologic confidence, into inferred, indicated, and measured categories.

In general, most statutory codes allow the reporting of mineral resources as inclusive of or separate from ore reserves, whereas some jurisdictions only allow separate reporting of additional mineral resources (e.g., the U.S. Securities and Exchange Commission requires mineral resources to be reported separately as "mineralized material"). The USGS categories of reserves and reserve base are broadly similar to ore reserves and mineral resources, respectively, although reserves base still excludes inferred resources. An analysis of various mineral resource reporting codes is given by Lambert et al. (2009).

In order to assess the long-term future of copper mining, the more realistic basis is to compile total mineral resources as reported by various companies and mines—that is, including all measured, indicated, and inferred resources. This is due to the fact that, at many of the world's giant or long-lived copper projects, ore reserves commonly represent a minority of the known geologic orebody, whereas mineral resources are sufficiently geologically understood to allow long-term project planning. Over time, it is very common for mineral resources to be upgraded to ore reserves and mined. Surprisingly, it appears that there are no formal studies published on this issue. A brief compilation is given in Table 2, based on extensive historical data sets for some major copper mines (e.g., Mudd, 2009a, b, 2010a, b, and analysis of company reporting), as well as other major projects, including the following:

1. Chino, USA: 1911 resources of 55.9 Mt at 2.24% Cu (McGraw-Hill, 1892–1940) and 1980 reserves of 402 Mt at 0.73% Cu (Cox et al., 1981), compared to 2011 ore reserves of 421 Mt at 0.42% Cu plus additional mineral resources of 356 Mt at 0.38% Cu, and a further 1,602 Mt at 0.26% Cu exists in stockpiles with an expected recovery of 11.4% (Freeport McMoRan Copper & Gold [FMCG], 2012).
2. Miami, USA: 1911 resources of 18.5 Mt at 2.58% Cu (McGraw-Hill, 1892–1940) compared to 2011 ore reserves of 60 Mt at 0.47% Cu plus additional mineral resources of 27 Mt at 0.47% Cu, and a further 460 Mt at 0.38% Cu exists in stockpiles with an expected recovery of 2.0% (FMCG, 2012).
3. Morenci, USA: 1928 resources of 113.0 Mt at 1.44% Cu (McGraw-Hill, 1892–1940) and 1980 reserves of 601 Mt at 0.80% Cu (Cox et al., 1981), compared to 2011 ore reserves of 4,250 Mt at 0.27% Cu plus additional mineral resources of 2,401 Mt at 0.26% Cu, and a further 4,957 Mt at 0.25% Cu exists in stockpiles with an expected recovery of 1.9% (FMCG, 2012).
4. Bingham Canyon, USA: 1911 and 1928 resources of 306.3 Mt at 1.53% Cu and 635 Mt at 1.066% Cu, respectively (McGraw-Hill, 1892–1940), and 1980 reserves of 1,453 Mt at 0.70% Cu (Cox et al., 1981), compared to 2011 ore reserves

TABLE 2. Ore Reserves, Mineral Resources, and Cumulative Production for Selected Major Copper Projects

Project	Operating period	Ore reserves	Additional mineral resources	Cumulative production[1]
Mt. Lyell, Australia	1896–2012[2]	1998: 27.6 Mt at 1.25% Cu 2010: 9.5 Mt at 1.24% Cu	nd 2010: 31.5 Mt at 1.17% Cu	1998–2010: 31.5 Mt at 1.23% Cu
Mt. Isa, Australia	1941–2012[2]	1990: 125 Mt at 3.4% Cu 2011: 55 Mt at 2.4% Cu	1990: 10 Mt at 3.0% Cu 2011: 342 Mt at 1.3% Cu	1990–2011: 123.3 Mt at 3.3% Cu
Olympic Dam, Australia	1988–2012[2]	1987: 460 Mt at 2.5% Cu 2011: 552 Mt at 1.84% Cu	1987: 1,448 Mt at 1.6% Cu 2011: 8,577 Mt at 0.80% Cu	1987–2011: 138.8 Mt at 2.35% Cu
Highland Valley, Canada	1962–2012[2]	1995: 503.9 Mt at 0.42% Cu 2011: 673.3 Mt at 0.29% Cu	1995: 229.3 Mt at 0.4% Cu 2011: 929.7 Mt at 0.26% Cu	1995–2011: 771.5 Mt at 0.38% Cu
Hudson Bay, Canada	1930–2012[2]	1928: 18 Mt at 1.71% Cu 2011: 29.3 Mt at 1.41% Cu	nd 2011: 14.0 Mt at 0.99% Cu	1928–2011: 147.1 Mt at 2.23% Cu
Quebrada Blanca, Chile	1995–2012[2]	1995: 99.5 Mt at 1.2% Cu 2011: 108.0 Mt at 0.39% Cu	1995: 225 Mt at 0.5% Cu 2011: 1,453 Mt at 0.47% Cu	1995–2011: 236.0 Mt at 0.92% Cu
Zaldivar, Chile	1995–2012[2]	1995: 280.6 Mt at 0.96% Cu 2011: 578 Mt at 0.52% Cu	1995: 311.5 Mt at 0.42% Cu 2011: 161.5 Mt at 0.47% Cu	1995–2011: 383.1 Mt at 0.83% Cu
Grasberg Group, Indonesia	1972–2012[2]	1988: 185 Mt at 1.57% Cu 2011: 2,523 Mt at 0.97% Cu	nd 2011: 2,386 Mt at 0.62% Cu	1988–2011: 1,331.4 Mt at 1.08% Cu

Notes: All reserve-resource data from company annual reporting (or government in the case of some data for Mt. Lyell and Hudson Bay); production reporting is updated from Mudd (2009a, b, 2010a, b); nd = no data

[1] For period of reserves noted only

[2] Still operating

of 915 Mt at 0.45% Cu plus additional mineral resources of 44 Mt at 1.78% Cu (Rio Tinto, 2012).

5. El Teniente, Chile: 1911 and 1928 resources of 10.2 Mt at 2.70% Cu and 242.6 Mt at 2.19% Cu, respectively (McGraw-Hill, 1892–1940), compared to 2011 ore reserves of 3,664 Mt at 0.87% Cu plus additional mineral resources of 12,985 Mt at 0.47% Cu, and a further 2,375 Mt at 0.537% Cu exists in stockpiles (Codelco, 2011).

In general, it is clear that, for the projects in Table 2 and listed above, the conversion of mineral resources to ore reserves over time is very successful. Furthermore, over the past 20 years, the increase in total mineable material (i.e., cumulative production plus remaining mineral resources) has been mainly driven by ongoing exploration and resource-to-reserve conversion, rather than just by technology or economics (although some technologies have seen greater uptake, such as heap leaching combined with solvent extraction and electrowinning, and increased prices in recent years have also been important for some projects).

Overall, mineral resources are a more robust basis to examine the future prospects of copper mining than ore reserves alone, and this would help to demonstrate more powerfully that there is sufficient known metal available for several decades, with strong prospects for continued growth in recoverable copper.

There are also methodologies for estimating "undiscovered resources" as well as projecting the likelihood of exploration success. A number of publications have used the grade, tonnage, and spatial occurrence density of known mineral deposits to assess the relationship between these variables to provide estimates and constraints on currently unknown resources; this approach is summarized well by Singer (2008) and is also discussed in a number of other publications (e.g., Singer et al., 2008; Shanks and Thurston, 2012). In particular, the USGS has a robust three-part quantitative assessment strategy (Cunningham et al., 2008; Singer, 1993, 1995, 2007) that involves delineation of permissive regions for individual mineral deposit types, development of grade-tonnage models appropriate for evaluating of individual geologic terranes or regions (e.g., Cox et al., 2007; Singer et al., 2008) and, finally, estimation of the number of undiscovered deposits (and, hence, undiscovered resources) in each given region (e.g., Shanks et al., 2009). Other, more speculative assessments have also been undertaken—for example, the estimation of global copper endowment and resources by the tectonically based assessment of known porphyry Cu deposits of Kesler and Wilkinson (2008). While these more speculative assessments might be useful in a broader scientific or public policy sense, statutory codes obviously do not support the reporting of such estimates and, given that the main focus of this paper is the compilation and assessment of discovered and delineated Cu resources rather than estimating potentially undiscovered resources, such literature and estimates will therefore be excluded.

For this paper, an extensive data set of total mineral resources containing Cu by individual project was compiled, as reported under statutory codes, and using 2010 data or the most recent report. In general, most exploration or mining project resources relate to a single deposit (e.g., Olympic Dam, Bingham Canyon), although some resources cover a group of individual orebodies or a mining camp (e.g., Oyu Tolgoi Group, Balkhash Complex). The compiled data set should be considered a reliable minimum geologic estimate (as of 2010), as the vast majority of resources contained within this compilation were reported under statutory codes (or similar). The full project list is provided as an electronic supplement. Whether all projects proceed to production, however, is dependent on economics, mining conditions, processing characteristics, site-specific environmental issues (especially land use and water and mine waste management), social constraints (e.g., bans on mining in high conservation value areas), energy sources and costs, etc.

Results and Analysis

The totals by country for our compiled Cu resources are shown in Table 3, including 2010 production, cumulative production from 1800 to 2010, and the ratio of resources to cumulative production. Our compiled data have a total of 730 projects with a total of 363.3 billion tonnes (Gt) of ore, grading 0.49% Cu and containing 1,780.9 Mt of Cu. In addition, China is reported to have 80.4 Mt Cu in national resources (Hongtao et al., 2011) while, for some countries with important Cu resources, we have old, minimal, or no data (e.g., Iran, Brazil). Combining our data with the Chinese national resources gives at least 1,861 Mt Cu globally—some 90 years' supply at the 2010 annual production rate of ~16 Mt of Cu metal per year (assuming an 80% recovery rate). This assessment of 2010 resources is some 343.2 Mt of Cu greater than the 1,518.1 Mt of Cu determined by Singer (1995), who used average deposit grades and associated tonnages based on production, reserves, and resources at the lowest possible cutoff grades. Even considering the 15 years between these studies, the fact that Singer's 1995 total included past production as well as reserves and resources means that the currently known total of Cu resources is significantly higher than previous assessments of global copper resources. However, the total copper resources presented here are about 0.062% of the assessed theoretical minimum global copper endowment of Kesler and Wilkinson (2008), who estimate that of this minimum 3×10^{11} t of Cu, some 8.9×10^{10} t of Cu may be recoverable, although this estimate is, by its very nature, highly speculative. This suggests that our total of at least 1,861 Mt of contained Cu in known resources makes up only 0.2% of the potential total recoverable Cu; although some of this copper has already been extracted (estimated at 577 Mt Cu, or 0.06% of the total recoverable Cu of Kesler and Wilkinson, 2008; see Schodde, 2010), this suggests that there may still be a substantial amount of undiscovered, recoverable Cu exclusive of the known 1,860 Mt of Cu already contained within mineral resource estimates.

The trends over time for USGS reserves and reserves base for Chile, the United States, and the world with national data for Australia and Canada are shown in Figure 1. The last USGS global reserves base estimate was 1,000 Mt Cu (for 2008) with a 2010 global reserves estimate of 630 Mt Cu (2011 was 690 Mt Cu). If one examines reported 2010 ore reserves only for operating mines and projects with reported reserves in Chile (38 projects), as well as allowing for recovery rate (based on a recent 5-year average), a value of 132.5 Mt

TABLE 3. Our 2010 Compiled Cu Resource Data, 2010 Production, Cumulative Country Production (1800–2010), and Ratio of Resources/2010 Production

	Our compilation (2010)					Cumulative production	Resources/ 2010 production/
Country	Mt ore	% Cu	Mt Cu	No. of projects	2010 (kt Cu)	(Mt Cu)	(years)
Chile	122,767.9	0.54	658.20	51	5,418.9	126.8	121.5
USA	49,427.5	0.34	170.11	56	1,110	108.9	153.3
Peru	35,088.1	0.48	168.20	52	1,247.2	25.1	134.9
Australia	20,292.4	0.63	126.89	149	849	22.2	149.5
China					~1,195	18.4	67.3
Russia	5,516.5	1.07	59.17	14	703	47.1	84.2
Mexico	17,369.4	0.33	56.71	30	270.1	13.7	210.0
Canada	17,660.7	0.31	54.12	95	498.4	40.9	108.6
DRC	2,288.9	2.34	53.64	21	~380	20.8	141.2
Mongolia	6,265.0	0.80	50.09	2	126.1	3.62	397.2
Indonesia	7,367.9	0.67	49.61	5	872.3	16	56.9
Zambia	4,524.3	1.03	46.74	19	690	35.3	67.7
Kazakhstan	6,682.0	0.47	31.22	7	380	7.05	82.2
Poland	1,539.0	2.00	30.77	4	425.4	15.6	72.3
Argentina	7,817.6	0.37	28.76	9	140.3	2.33	205.0
Papua New Guinea	5,611.9	0.48	26.83	14	159.8	7.08	167.9
Philippines	5,363.3	0.47	25.10	13	58.4	7.12	429.8
Pakistan	5,867.8	0.41	24.06	1	18	0.138	1,336.7
Panama	6,465.0	0.30	19.36	1	nd	0.183	nd
Brazil	2,855.8	0.56	16.10	12	214.2	2.14	75.2
South Africa	14,610.3	0.08	11.66	39	102.6	9.11	113.6
India[1]	1,394.4	0.82	11.42	14	33	1.81	346.1
Iran	1,200.0	0.70	8.40	1	257	3.6	32.7
Fiji	2,287.7	0.35	8.01	1	nd	0.0001	nd
Botswana	1,287.7	0.51	6.59	9	~31	12.2	nd
Sweden	2,620.0	0.23	5.97	18	76	3.31	78.6
Afghanistan	240.0	2.30	5.52	1	nd	nd	nd
Finland	2,197.7	0.19	4.28	31	14.7	1.81	291.2
Laos	399.8	0.80	3.20	3	132	nd	24.2
Zimbabwe	2,138.5	0.11	2.41	4	~4	0.91	nd
Romania	431.0	0.55	2.37	1	~1	1	nd
Spain	238.5	0.89	2.11	4	20.6	2.64	102.4
Portugal	73.8	2.57	1.89	1	74.3	2.5	25.4
Namibia	182.4	0.84	1.53	10	nd	1.77	nd
Eritrea	122.2	1.07	1.31	5	nd	nd	nd
Saudi Arabia	83.1	1.35	1.12	3	~2	0.015	nd
Greece	192.2	0.55	1.06	2	nd	0.015	nd
Thailand	200.0	0.51	1.02	2	nd	nd	nd
Kyrgyzstan	442.2	0.21	0.92	2	nd	nd	nd
Dominican Republic	421.9	0.21	0.88	3	9.2	nd	95.7
Venezuela	556.9	0.13	0.71	1	nd	0.015	nd
Burkina Faso	227.2	0.27	0.61	1	nd	0.0001	nd
Turkey	37.6	1.36	0.51	2	97	2.41	5.3
Tanzania	147.2	0.29	0.42	3	5.3	0.046	79.2
Mauritania	25.5	1.39	0.35	1	37	0.23	9.5
Burundi	185.0	0.17	0.31	1	nd	nd	nd
Bolivia	491.3	0.05	0.24	2	2.1	0.438	114.3
Algeria	18.1	0.65	0.12	2	nd	0.02	nd
Ecuador	3.1	3.33	0.10	1	nd	0.03	nd
Mozambique	3.1	1.40	0.04	1	nd	0.0073	nd
Norway	13.8	0.25	0.04	3	nd	1.41	nd
Vietnam	21.8	0.13	0.03	1	nd	0.07	nd
Ireland	3.6	0.70	0.03	1	nd	0.134	nd
UK	1.3	1.08	0.01	1	nd	0.901	nd
Total	363,269.9	0.49	1,780.9	730	~15,655	566.9	

Notes: 2010 production data from Edelstein (2012) and Bureau of Resource & Energy Economics (2011); cumulative production data compiled from McGraw-Hill, 1892–1940, US Bureau of Mines (1933–1993), USGS (1996–2011, 1994–2010), Australian Bureau of Agricultural and Resource Economics (1995–2010), Houston (1904), Culver and Reinhart (1989), Mudd (2009a), Kelly and Matos (2012), and company data (for PNG); note that some countries have data gaps, but these are minor and often in the 1800s, when annual production was very low; nd = no data

[1] Indian data are subtotals by state only (Indian Bureau of Mines, 1958–2010), because only a fraction of individual projects are reported publicly

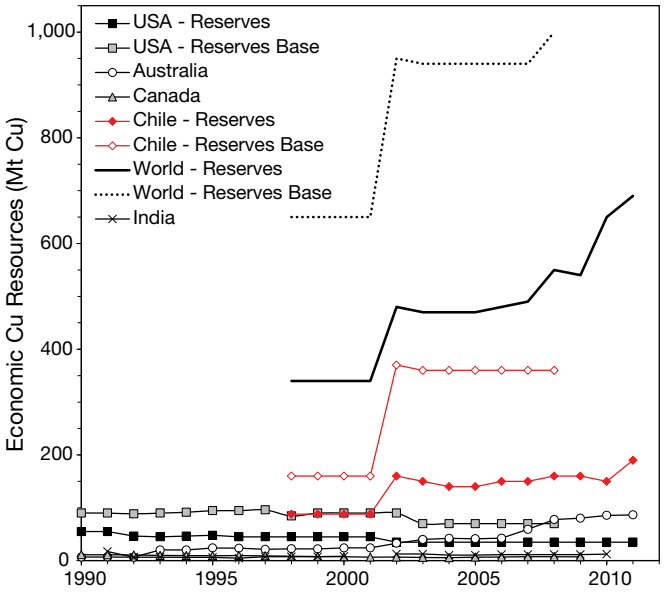


FIG. 1. Cu reserves and resources over time for Australia, Canada, Chile, the United States (Mudd and Weng, 2012), and India (Indian Bureau of Mines, 1958–2010).

Cu can be derived. For total mineral resources, allowing for recovery at these projects gives 491.8 Mt Cu, which still excludes 13 other major projects with a contained copper of 75 Mt Cu (i.e., ~60 Mt Cu at 80% recovery). Similar data analyses for Canada, Australia, Peru, and the United States also show that recoverable Cu in total mineral resources is generally much higher than USGS reserves base estimates, which can be expected given that reserves base still excludes inferred resources.

Our data indicate that, in terms of Cu resources in individual countries, Chile has the largest Cu resources of ~658 Mt Cu—more than double the Chilean resources, reserves, and past production total of Singer (1995)—followed by the United States, Peru, and Australia with 170.1, 168.2, and 126.9 Mt Cu, respectively. Our order of endowment differs from that of Singer (1995), who listed Chile, the United States, Zaire (present-day Democratic Republic of the Congo), Canada, Zambia, and Australia in order of decreasing total Cu production, resources, and reserves. The different order arguably reflects the amount of past production, as well as ongoing exploration success and recent increases in Cu demand and price. The data in Table 3 also shows the value of strong public mineral resource reporting codes and practices, because the major mining countries of Chile, the United States, Australia, Canada, Peru, and South Africa are well represented by high numbers of Cu projects.

In comparing cumulative Cu production with reported resources for countries with available data, it is evident that most countries have remaining Cu resources higher than cumulative production. Although some countries are close in this regard (e.g., USA, Canada), major Cu producers, such as Chile, still have substantially more Cu resources than cumulative production. A few countries have very minor resources remaining relative to modest past production (e.g., United Kingdom, Norway, Ireland).

The relationship between ore grades and mineral resources is shown in Figure 2, with contained Cu versus ore grade shown in Figure 3; both graphs are sorted by deposit type. In both graphs, porphyry projects dominate mineral resources and contained Cu, whereas sediment-hosted projects typically have the highest ore grades. Other deposit types, such as iron oxide copper-gold (IOCG) or volcanogenic massive sulfide (VMS) deposits, have varied grades and resources, whereas magmatic

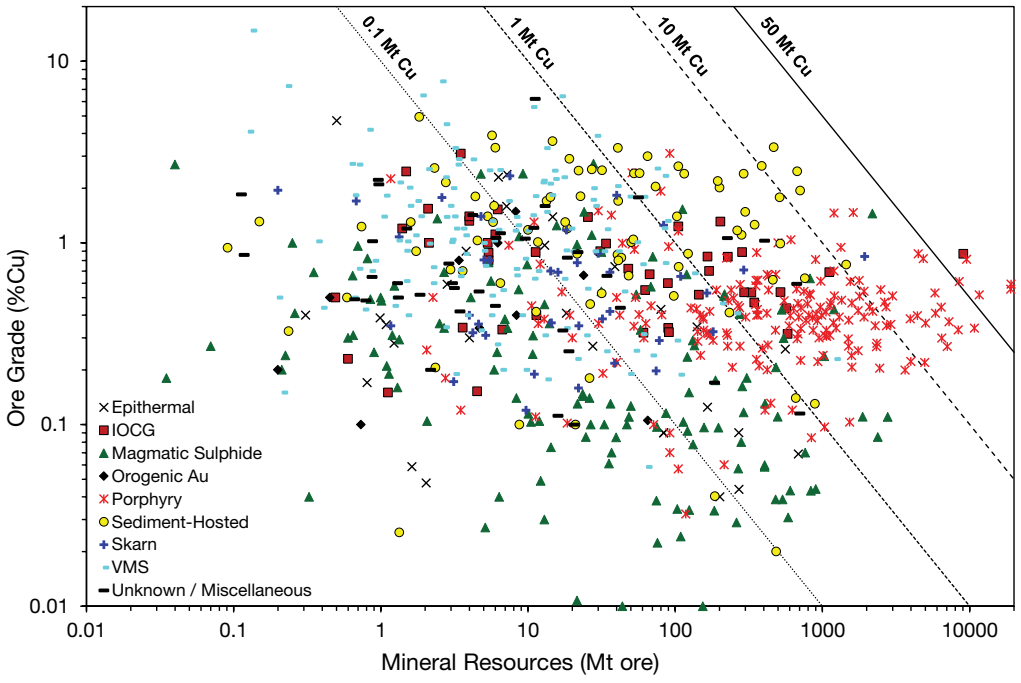


FIG. 2. Ore grades versus mineral resources by deposit types.

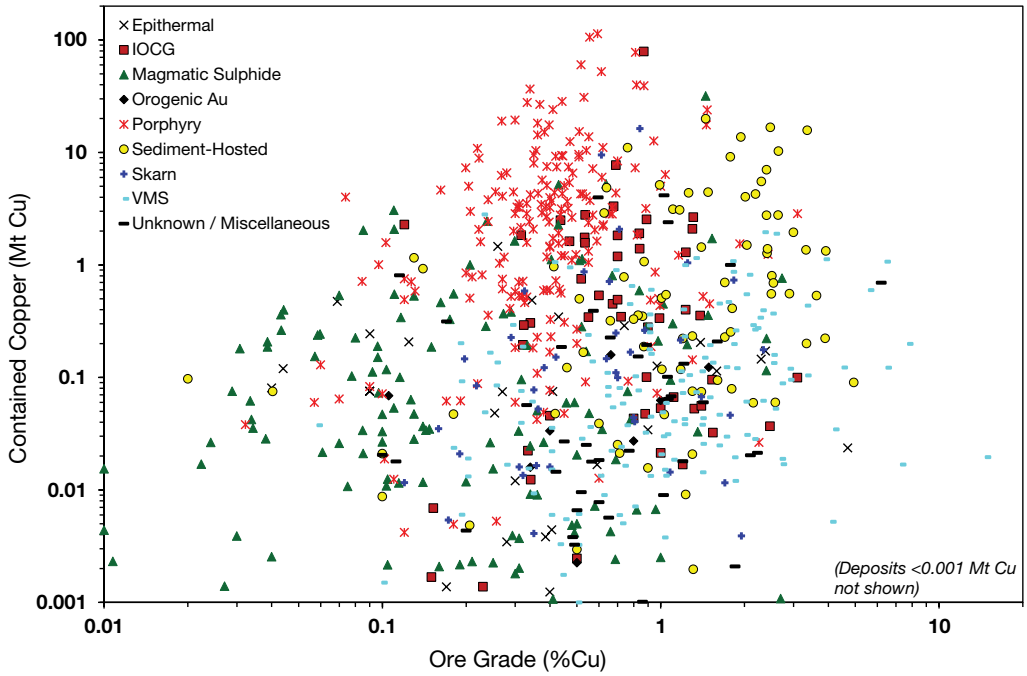


FIG. 3. Contained copper versus ore grades by deposit types.

sulfide deposits typically contain low concentrations of Cu and commonly have smaller resources. Cumulative frequency curves by ore grade and contained Cu are presented in Figure 4, showing a median project size of 0.194 Mt Cu and median project ore grade of 0.51% Cu. About 3.2% of projects have an ore grade greater than 3% Cu, whereas ~72.7% have an ore grade lower than 1% Cu. In addition, ~5% of projects have more than 10 Mt Cu, whereas ~71.4% have less than 1 Mt Cu.

The 25 largest projects are shown in Table 4, including their cumulative production to 2010, where available. Porphyry deposits constitute eight of the top 10 largest projects, and 19 out of the top 25. The ore grade in these 25 projects varies widely, ranging from 0.30% Cu at Cobre Panama to 3.36% Cu at Kamoto Group, with an average of 0.59% Cu. All but two projects have mineral resources reported in billions of tonnes. Although only eight projects report gold grades, ranging from 0.04 to 0.71 g/t, some projects do not report gold grades in mineral resources but extract minor amounts of gold (and silver) during processing (e.g., Escondida; see BHP Billiton Ltd, 2011a). Importantly, these 25 projects alone contain

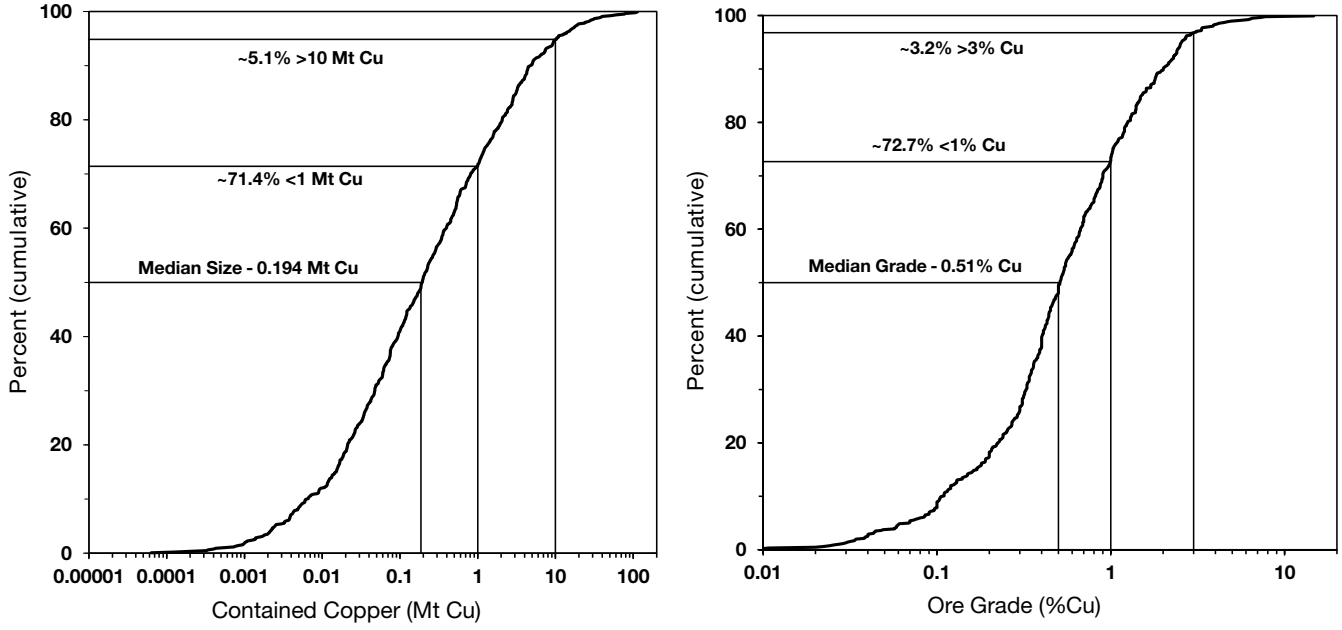


FIG. 4. Cumulative frequency curves for contained copper (left) and ore grades (right).

TABLE 4. Largest 25 Cu Projects by Contained Cu

Mine name	Status	Deposit type	Mt ore	% Cu	Au g/t	Ag g/t	Other	Mt Cu	Disc.	Start prod.	Cum. prod. (Mt Cu)[1]	Company (% ownership)
Andina, Chile	Op.	Porphyry	19,162	0.59				113.63	1920	1970	5.85	Codelco (100%)
El Teniente, Chile	Op.	Porphyry	19,040	0.56				105.85	<1900	1904	24.63	Codelco (100%)
Olympic Dam, Australia	Op.	IOCG	9,075	0.87	0.32	1.50	0.27% U_3O_8	78.95	1975	1988	3.00	BHP Billiton (100%)
Collahuasi, Chile	Op.	Porphyry	9,554	0.81				77.54	<1900	1999	5.44	Anglo American (44%), Xstrata (44%), Mitsui Consortium (12%)
Chuquicamata, Chile	Op.	Porphyry	11,631	0.52				60.15	<1900	1910	54.98	Codelco (100%)
Escondida, Chile	Op.	Porphyry	8,509	0.61				52.13	1981	1990	18.21	BHP Billiton (57.5%), Rio Tinto (30%), JECO (10%), IFC (2.5%)
Grasberg Group, Indonesia	Op.	Porphyry/skarn	4,855	0.82	0.71	3.78		39.75	1988	1990	13.09	Freeport-McMoRan (~82.2%), Rio Tinto (~8.4%), Indonesian government (~9.4%)
Oyu Tolgoi Group, Mongolia	Dev.	Porphyry	4,485	0.87	0.35			39.05	2001	nd	nd	Ivanhoe-Rio Tinto JV
Pebble, United States	Dep.	Porphyry	10,777	0.34	0.31			36.56	1988	nd	nd	Northern Dynasty JV
Taimyr Peninsula, Russia	Op.	Magmatic sulfide	2,188	1.45	0.22			31.74	<1900	1939	12.28	Norilsk Nickel (100%)
Los Pelambres, Chile	Op.	Porphyry	5,818	0.53	0.04		0.01% Mo	30.84	1920s	1999	4.29	Antofagasta (100%)
Los Bronces, Chile	Op.	Porphyry	6,420	0.44				28.39	<1900	~1916	4.20	AngloAmerican (75.5%), Codelco (24.5%)
Buenavista del Cobre, Mexico	Op.	Porphyry	8,388	0.33				27.80	1890s	1899	insufficient data	Southern Copper Corp. (100%)
Radomiro Tomic, Chile	Op.	Porphyry	7,247	0.37				26.67	1950s	1998	see Chuq.[2]	Codelco (100%)
Reko Diq, Pakistan	Dep.	Porphyry	5,868	0.41	0.22			24.06	2006	nd	nd	Antofagasta (37.5%), Barrick Gold (37.5%), Balochistan State government (25%)
Resolution, United States	Dep.	Porphyry	1,624	1.47			0.037% Mo	23.87	~1994	nd	nd	Rio Tinto (55%), BHP Billiton (45%)
Udokan, Russia	Dep.	Sed.-hosted strat. Cu	1,375	1.45		8.65		19.95	1949	nd	nd	Baikal Mining Company (100%)
Cobre Panama, Panama	Dev.	Porphyry	6,465	0.30	0.05	1.11	0.008% Mo	19.36	1968	nd	nd	Inmet Mining Corp. (80%), KPMC (20%)
Morenci, United States	Op.	Porphyry	7,070	0.27			0.002% Mo	19.00	1870s	1881	»10	Freeport-McMoRan (85%), Sumitomo (15%)
Toquepala, Peru	Op.	Porphyry	5,029	0.36				18.18	<1900	1960	6.09	Southern Copper Corp. (100%)
Cerro Verde, Peru	Op.	Porphyry	4,422	0.40		1.27	0.014% Mo	17.56	<1900	<1900	insufficient data	Freeport-McMoRan
Los Sulfatos, Chile	Dep.	Porphyry	1,200	1.46				17.52	~2007	nd	nd	Anglo American (75.5%), Codelco (24.5%)
Tenke Fungurume, DRC	Op.	Sed.-hosted strat. Cu	674	2.48			0.22% Co	16.69	1917	2009	0.19	Freeport-McMoRan (57.75%), Lundin Mining (24.75%), Gécamines (17.5%)
Antamina, Peru	Op.	Skarn	1,934	0.84		10.7	0.44% Zn, 0.026% Mo	16.29	<1900	2001	3.07	BHP Billiton (33.75%), Xstrata (33.75%), Teck (22.5%), Mitsubishi (10%)
Kamoto Group, DRC	Op.	Sed.-hosted strat. Cu	468	3.36			0.41% Co	15.71	1930s	1942	insufficient data	Katanga Mining (82.5%), Gécamines (17.5%)
		Totals	163,278	0.49				957.27				

Notes: Dep. = deposit is in the exploration stage, Dev. = Development is under construction with commercial production expected in the near future (~1–3 years), Disc. = discovery year, JV = joint venture, Op. = operating is in active production; nd = no data

[1]Cum. prod.: cumulative production (to 2010 only) is primarily sourced from company reports or available technical literature (e.g., USGS, 1996–2011, 1994–2010); some data courtesy of MinEx Consultants

[2]Cumulative production is included in Chuquicamata

~957 Mt of Cu—more than half of our global estimate of ~1,861 Mt Cu, and 18 of these large projects are in commercial operation, whereas only six are currently undeveloped, and one is in development. This suggests that medium-term expansion in global Cu production will need to come mainly from brownfield expansion, rather than greenfield projects, unless substantial new discoveries are made in the very near future.

The statistics for all projects by deposit type are summarized in Table 5. For the dominant deposit types, the 10 largest projects are shown in Table 6. The IOCG, magmatic sulfide, skarn, and sediment-hosted Pb-Zn mineral deposit categories are all dominated by one or two projects that contain Cu resources between six and 10 times larger than the project with the next-largest Cu resources. In comparison, the porphyry, VMS, and epithermal deposit categories have less skewed Cu resource distributions, even considering the wide variations in sizes and grades of both VMS and epithermal deposits.

It should be noted that although reliance on published resources with methodologies dictated by public mineral resource reporting codes and practices allows an accurate and, more importantly, precise assessment of existing global copper resources, there still remain a number of issues concerning the allocation of resources to individual mineral deposit types. One example is provided by the Grasberg mining complex, where, although the majority of the resource has been defined by Freeport as porphyry related, a closer inspection of the data reveals that the global Grasberg resource contains a significant amount of skarn-related ore. This is exemplified by the Big Gossan resource, which currently contains 56 Mt of skarn ore at 2.18% Cu (Meinert et al., 1997; FMCG, 2012). If this resource were separated from the global Grasberg resource and discussed here as a separate skarn resource, it would rank as the fourth largest global skarn-type Cu deposit in Table 6. Given that part of the Deep Ore Zone resource at Grasberg is also partly skarn related, the total Grasberg skarn resource probably constitutes a major percentage of the total global Grasberg Cu resource. The initial ore reserves for the Ok Tedi project of 414.7 Mt ore at 0.76% Cu and 0.73 g/t Au included a leached gold cap of 18 Mt ore, 348.9 Mt of porphyry ore, 19 Mt of oxide ore, and 28.8 Mt skarn ore (Davies, 1992). However, current mineral resource reporting codes and practices require separation of mineral resources that are processed in different ways, but not mineral resources that are generated by differing geologic processes (e.g., skarn vs. porphyry). Similar situations also exist at Bingham Canyon, Ok Tedi, Santa Rita, and Morenci, among others, where significant amounts of skarn-related Cu ore may be reported as porphyry

TABLE 5. Total Mineral Resources by Deposit Type, Including Deposit Type Means and Medians

Deposit type	Variable	Ore (Mt)	% Cu	g/t Au	% Ni	Cu (Mt)
Porphyry	Total	291,016.0	0.45	0.09		1,316.54
(200 projects)	Median	553.7	0.40	0.27		2.24
	Mean	1,455.1	0.48	0.40		6.58
	Std. Dev.	2,672.8	0.39	0.54		14.53
Sediment-hosted Cu	Total	10,873.9	1.52	0.01		165.45
(62 projects)	Median	42.1	1.54	0.27		0.62
	Mean	175.4	1.75	0.27		2.67
	Std. Dev.	297.2	1.05	0.26		4.48
Iron oxide copper-gold (IOCG)	Total	17,730.3	0.71	0.25		125.10
(51 projects)	Median	60.8	0.70	0.32		0.34
	Mean	347.7	0.84	0.81		2.45
	Std. Dev.	1,287.9	0.55	1.81		11.01
Magmatic sulfide	Total	26,542.6	0.29	0.13	0.24	76.21
(133 projects)	Median	30.3	0.20	0.14	0.31	0.05
	Mean	199.6	0.39	0.19	0.58	0.57
	Std. Dev.	439.8	0.51	0.33	0.66	2.84
Skarn	Total	4,901.0	0.70	0.04		34.45
(39 projects)	Median	18.2	0.64	0.60		0.10
	Mean	125.7	0.74	1.00		0.88
	Std. Dev.	387.8	0.56	1.85		2.96
Volcanogenic massive sulfide	Total	4,042.1	0.78	0.31		31.56
(144 projects)	Median	6.4	1.03	0.65		0.07
	Mean	28.1	1.51	1.02		0.22
	Std. Dev.	106.5	1.75	1.07		0.40
Other/miscellaneous	Total	2,701.1	0.59	0.28		15.97
(50 projects)	Median	6.0	0.63	1.52		0.03
	Mean	54.0	0.88	1.82		0.32
	Std. Dev.	147.2	0.93	1.44		0.86
Sediment-hosted Pb-Zn	Total	2,745.9	0.39	0.002		10.67
(21 projects)	Median	21.0	0.60	0.25		0.07
	Mean	130.8	0.70	0.36		0.51
	Std. Dev.	248.0	0.58	0.34		1.07
Epithermal	Total	2,717.0	0.18	0.20		4.91
(30 projects)	Median	13.9	0.32	0.89		0.08
	Mean	90.6	0.67	2.53		0.16
	Std. Dev.	166.1	0.98	5.18		0.28

Notes: Std. dev. = standard deviation; ore grades in totals are weighted averages (mean is arithmetic average)

TABLE 6. Largest 10 Projects by Deposit Type and Contained Cu

		I	II	III	IV	V	VI	VII	VIII	IX	X
Porphyry	Project	Andina	El Teniente	Collahuasi	Chuquicamata	Escondida	Grasberg Group	Oyu Tolgoi Group	Pebble	Los Pelambres	Los Bronces
	Mt ore	19,162	19,040	9,554	11,631	8,509	4,855	4,485	10,777	5,818.4	6,419.8
	% Cu	0.593	0.556	0.81	0.517	0.61	0.82	0.87	0.34	0.53	0.44
	Mt Cu	113.63	105.85	77.54	60.15	52.13	39.75	39.05	36.56	30.84	28.39
IOCG	Project	Olympic Dam	Salobo	Mina Justa	Candelaria	Carrapateena	Prominent Hill	Mt. Elliott	Marcona	Igarape Alemão	El Soldado
	Mt ore	9,075	1,116	488.8	520	203	285.4	570	1,900	161	227.8
	% Cu	0.87	0.69	0.68	0.54	1.31	0.89	0.44	0.12	1.3	0.84
	Mt Cu	78.95	7.70	3.31	2.79	2.66	2.54	2.49	2.28	2.09	1.91
Magmatic sulfide	Project	Taimyr Peninsula	Nokomis-Duluth	Mesaba	Mogalakwena	NorthMet	Spruce Road	Zimplats	Bokoni	Sudbury (Vale Inco)	Kola Peninsula
	Mt ore	2,188.4	823.8	1,200	2,779.9	1,029	529.5	1,879	2,382.4	112.3	546.3
	% Cu	1.45	0.64	0.43	0.11	0.24	0.43	0.11	0.09	1.53	0.30
	Mt Cu	31.74	5.25	5.16	3.06	2.45	2.27	2.07	2.03	1.72	1.63
Skarn	Project	Antamina	Las Bambas	Bystrinskoye	El Brocal West	PUT 1	El Brocal North	Lugokanskaya	Kultuminskaya	Rondoni	Buenavista Zinc
	Mt ore	1,934.3	1,550	292	83.4	164	40.0	109	181	30.0	36
	% Cu	0.84	0.61	0.71	1.25	0.53	1.83	0.65	0.32	0.88	0.69
	Mt Cu	16.29	9.49	2.07	1.04	0.87	0.73	0.71	0.59	0.26	0.25
VMS	Project	Harper Creek	East Region	Neves Corvo	San Nicolas	Ambler	Nifty	Las Cruces	Mankayan	Ruttan	Rio Tinto
	Mt ore	1,224.9	83.6	73.8	87.0	28.9	60.3	16.7	257.8	82.6	205.2
	% Cu	0.23	2.34	2.57	1.32	3.88	1.79	6.42	0.41	1.21	0.46
	Mt Cu	2.81	1.96	1.89	1.15	1.12	1.08	1.07	1.06	1.00	0.95
Sed.-hosted stratiform Cu	Project	Udokan	Tenke Fungurume	Kamoto Group	Konkola	Trident	Polkowice-Sieroszowice	Rudna	Głogów Głęboki-Przemysłowy	Aynak	Kansanshi
	Mt ore	1,375.2	673.9	467.6	706	1,450	387	513	292	240	517.9
	% Cu	1.45	2.48	3.36	1.94	0.76	2.65	1.78	2.40	2.3	0.99
	Mt Cu	19.95	16.69	15.71	13.71	11.02	10.26	9.13	7.01	5.52	5.13
Sed.-hosted strat. Pb-Zn	Project	Mt. Isa	Mt. Isa (open cut)	Kuusilampi	Kolmisoppi	Lady Annie	Swartberg	Berenguela	Black Mountain	Malku Khota	Dugald River
	Mt ore	200	283	890	660	40.5	48.3	21.6	26.5	485	4.4
	% Cu	2.01	1.11	0.13	0.14	0.86	0.66	0.87	0.46	0.02	1.8
	Mt Cu	4.03	3.13	1.16	0.92	0.35	0.32	0.19	0.12	0.10	0.08
Epithermal	Project	Yanacocha-Conga	Bayaguana Group	Pascua-Lama	KTL	Kazakhmys Gold Group	Pueblo Viejo	Cerro de Pasco	Cozamin	Marcapunta	San Vicente
	Mt ore	560.5	140.9	687.8	80	39.0	270.4	166.0	14.7	7.2	6.3
	% Cu	0.26	0.34	0.07	0.43	0.74	0.09	0.12	1.39	2.38	2.30
	Mt Cu	1.46	0.49	0.47	0.34	0.29	0.24	0.21	0.20	0.17	0.15

type (L. Meinert, pers. comm.; Jowitt et al., 2013); however, how to define these skarn resources separately while still retaining the robust approach of using published resources defined by methodologies dictated by strong public mineral resource reporting codes and practices is currently unclear.

A similar situation exists with IOCG deposits, where we have attempted to separate other deposits that have previously been classified as IOCG deposits, such as Fe- or Cu-rich skarns and carbonatite-hosted mineralization (e.g., Williams et al., 2005), into other categories, where possible and where information allows, with the intention that within this paper an IOCG classification corresponds to the strict IOCG definition of Groves et al. (2010). However, it must be noted that in some cases, where information on a deposit is restricted, or where a mining or exploration company has used a sensu lato mineral deposit classification, a few minor IOCG deposits within our database could actually be skarns or carbonatite-related deposits. This highlights an area where future collaboration between economic geologists, mineral resource geologists, and engineers may prove fruitful in defining individual deposit types within a single global resource figure and allowing a clearer definition of the relative importance of individual ore-forming processes during mineral deposit generation.

Overall, the deposit type data sets presented herein are reasonably similar to previous studies for grades and tonnages, such as those of Cox and Singer (1986), Singer (1995), Gerst (2008), and Singer et al. (2008), among others, although it should be noted that refining grade-tonnage models is not the primary focus of this paper.

Average grades are highly variable in all categories in Table 6, barring porphyry Cu deposits—unsurprising given the nature of these bulk-tonnage deposits. No clear relationship between grade and tonnage for the 10 largest projects of any mineral deposit type is observed; the top 10 largest projects in all mineral deposit categories are a mixture of higher-grade and lower-tonnage, and lower-grade and higher-tonnage deposits. This is exemplified by the VMS category, where the deposit with the most contained Cu—Harper Creek—has nearly 15 times as much ore as the second-placed East Region mining camp, but at Cu grades ~10 times lower. The IOCG, skarn, sediment-hosted stratiform Cu, sediment-hosted Pb-Zn, and epithermal deposit categories have projects within the top 10 largest that have contained Cu below the average for the entire category. In some cases—for example, IOCG deposits—this is because the category is dominated by one super-large deposit, in this case, Olympic Dam. However, in other categories—for example, epithermal deposits—this is not the case; this suggests that the vast majority of epithermal deposits have low amounts of contained Cu, with only a few epithermal projects containing significant Cu resources.

To assess the importance of by-products (or co-products in some cases), the economic value of reported metals for all projects was calculated based on 2010 average metal prices (USGS, 1996–2011); the 25 most valuable projects are shown in Table 7. While the contained value for most projects is dominated by Cu, for others the critical importance of by/co-products such as platinum group elements (PGEs), gold, molybdenum, or cobalt is clear (e.g., PGEs at Bokoni, Mogalakwena, Marikana, Zimplats, and Tumela; uranium-Au at Olympic Dam; Co at Tenke Fungurume; and Au at Grasberg and Pebble). Despite Olympic Dam being the third largest

TABLE 7. Largest 25 Resources Ranked by Largest Combined Value (US$ billion), Including By-Products and Proportional Value (%)

Project	Value	Cu (%)	Au (%)	Ag (%)	Mo (%)	Other (%)
Olympic Dam	977.34	60.9	11.7	0.9	0.0	26.5 (U_3O_8)
Taimyr Peninsula	878.24	27.2	2.2	0.0	0.0	41.7 (Ni), 28.9 (Pt + Pd + Rh)
Andina	855.99	100.0	0.0	0.0	0.0	nd
El Teniente	797.42	100.0	0.0	0.0	0.0	nd
Bokoni	628.84	2.4	4.1	0.0	0.0	16.8 (Ni), 76.6 (Pt + Pd + Rh)
Collahuasi	584.12	100.0	0.0	0.0	0.0	nd
Chuquicamata	453.11	100.0	0.0	0.0	0.0	nd
Grasberg Group	448.09	66.8	30.5	2.7	0.0	nd
Pebble	407.06	67.7	32.3	0.0	0.0	nd
Escondida	392.73	100.0	0.0	0.0	0.0	nd
Oyu Tolgoi Group	355.54	82.7	17.3	0.0	0.0	nd
Cumo	343.04	8.8	0.0	77.4	13.8	nd
Zimplats	334.11	4.7	5.9	0.0	0.0	16.3 (Ni), 73.1 (Pt + Pd + Rh)
Mogalakwena	331.87	6.9	4.5	0.0	0.0	32.9 (Ni), 55.7 (Pt + Pd + Rh)
Los Pelambres	261.75	88.7	3.5	0.0	7.7	nd
Los Bronces	234.99	91.0	0.0	0.0	9.0	nd
Reko Diq	232.16	78.1	21.9	0.0	0.0	nd
Marikana	221.59	1.4	2.6	0.0	0.0	7.7 (Ni), 88.3 (Pt + Pd + Rh)
Buenavista del Cobre	209.42	100.0	0.0	0.0	0.0	nd
Kamoto Group	205.60	57.6	0.0	0.0	0.0	42.4 (Co)
Radomiro Tomic	200.90	100.0	0.0	0.0	0.0	nd
Resolution	200.77	89.6	0.0	0.0	10.4	nd
Tenke Fungurume	193.16	65.1	0.0	0.0	0.0	34.9 (Co)
Cobre Panama	182.04	80.1	7.4	2.6	9.9	10.6 (Zn)
Tumela	173.82	0.9	1.2	0.0	0.0	10.6 (Ni), 87.2 (Pt + Pd + Rh)

Note: Economic values are based on 2010 price data from USGS (1996–2011) or Australian Bureau of Agricultural and Resource Economics (1995–2010), and are intended to be indicative only; nd = no data

Cu resource, it dominates the contained value statistics due to its contained Au and U. Curiously, the Olympic Dam deposit also contains Co at a grade of ~0.03% Co (Mudd et al., submitted), worth some $126 billion, as well as rare earth elements (REEs) at an approximate grade of about 0.75% REE oxides[1] (see Williams and Pollard, 2001; Geoscience Australia, 2012). Although the REEs are worth some $3,000 billion alone (based on recent prices for REE mixtures), more than triple the combined value of the contained Cu-U-Au-Ag, current owner BHP Billiton claims that REEs (and Co) are uneconomic to extract from Olympic Dam (BHP Billiton Ltd, 2011b).

For selected major Cu producers—major either in scale or in importance in their deposit type—reported mineral resources were compiled from 1990 to 2011 (Fig. 5). For most porphyry projects, the contained Cu within the project continues to grow substantially, while ore grades gradually decline. In contrast, the Bingham Canyon and Highland Valley porphyry Cu projects have somewhat stable contained Cu resources but a declining ore grade over more recent years (since about 2005), most likely due to improved demand and market prices allowing a lowering of the cutoff grade (including by/co-product value), alongside mine redesign, optimization, and reinvestment. At Grasberg, the grade drops in 2004 due to the addition of mineralized material to ore reserves. For IOCG, magmatic sulfide, skarn, sediment-hosted, and VMS deposits, the ore grades over time are generally relatively stable or show a very gradual decline, whereas contained Cu is typically stable (despite mining), except for remarkable growth at Olympic Dam.

Discussion: Assessing Copper Resources

The extensive data compiled in this paper raise a number of issues and provide sound quantitative evidence that has often been missing from debates regarding mineral resources.

The concept of globally recoverable mineral resources was addressed systematically by Skinner (1976), who formalized the concept of the "mineralogical barrier" for geochemically scarce metals (Fig. 6). The mineralogical barrier represents the point at which energy costs become prohibitive to extract a particular metal, often due to changes in host mineralogy from, say, sulfides to silicates. For Cu, Skinner (1976) estimated that the mineralogical barrier was ~0.1% Cu, although this was a very approximate value. As can be seen from our results, Figure 3 closely resembles the "current mining" part of Figure 6. Existing mines are operating across ore grades from 0.05% to 9.4% Cu, with an average ore grade of ~0.62% Cu and all mines below 0.25% Cu producing Cu as a by- or co-product (Mudd and Weng, 2012). Importantly, the global average resource grade of our data set is 0.49% Cu, which is still very close to the average ore grade of current mining and well above Skinner's ~0.1% Cu mineralogical barrier. It should be noted, of course, that current mineral resources are investigated and quantified based on existing technology and reasonable economic assumptions concerning present and future prices, demand, supply, and so on. As such, our data provide a sound, empirical validation of Skinner's conceptualization of recoverable mineral resources. Norgate and Jahanshahi (2010) recently showed that the energy intensity of Cu production begins to increase as ore grades approach 1% Cu and grows exponentially below 0.25% Cu. This suggests that the concept of a "0.1% Cu mineralogical barrier" for Cu mining appears reasonable (although factors such as market prices, energy costs, recycling, and so on would also need to be considered). Finally, our data compilation suggests that Cu mining is still some decades away from approaching 0.1% Cu.

The variation of economic Cu mineral resources over time for Canada, Chile, Australia, and the United States was shown in Figure 1. Recently, Schodde (2010) presented a detailed historical analysis of Cu resources, using an approach similar to that of this paper, albeit with a much more comprehensive historical reserve-resource database (Fig. 7). Importantly, both graphs demonstrate that global Cu resources have continued to grow throughout the 20th century; although Canada, at first, appears to be an exception, the significantly different estimates in Tables 1 and 3 should be noted. Furthermore, our 2010 Cu resource data of ~1,861 Mt Cu (including China) is close to Schodde's remaining resource of 2,459 Mt Cu (i.e., 3,145 Mt Cu minus 686 Mt Cu contained in mining to date, with 577 Mt Cu recovered; Schodde, 2010). Given that many of the giant or supergiant Cu projects have resources that are still increasing (e.g., Olympic Dam, Escondida, Andina, among others), it is clear that there is still substantial room for growth in global economic Cu resources.

Arguably, one of the most important drivers behind the growth in Cu resources over time is the lowering of cutoff grades for ore that can be processed. As economic ore grades decrease, the amount of contained Cu within a deposit often increases substantially, especially for porphyry deposits, which rely on bulk tonnage and contain ore at low to medium Cu grades. Cutoff grades can vary according to a number of project-specific factors, such as electricity costs, transport, project and technology configuration, co/by-products, and so on, but have clearly been declining throughout the 20th century. Schodde (2010) argues that the grades of processed ore are now converging toward cutoff grades, reflecting technological innovation, which has driven down unit mining and processing costs. Cutoff grades are commonly assessed as copper equivalent (Cu equiv), which includes by/co-product values as equivalent Cu value. For open-cut mines, common cutoff grades range between 0.05 and 0.5% Cu equiv (e.g., Codelco, Teck, Xstrata), depending on processing configuration (mill, heap leach) or ore type (oxide, sulfide), while underground mines can range from 0.5 to 1.85% Cu equiv (e.g., Freeport, Xstrata; see the respective company annual reports). Many projects also use a variable cutoff grade model, which takes into account a variety of site-specific factors, such as metallurgical recoveries, by/co-product extraction and prices, input costs, or mining dilution, among others. In general, it would appear that cutoff grades, while still significantly above Skinner's mineralogical barrier of ~0.1% Cu, are gradually approaching this value, especially given the dominance of open-cut mining (see Mudd and Weng, 2012).

Throughout the 20th century, Cu prices in real terms have gradually declined, even allowing for numerous boom-bust

[1] At Olympic Dam, average ore grades include approximately 0.2% La and 0.3% Ce (or ~0.26% La_2O_5 and ~0.39% Ce_2O_5), with a total of some 53 Mt contained REE oxides (p. 77, Geoscience Australia, 2012; also see Reeve et al., 1990).

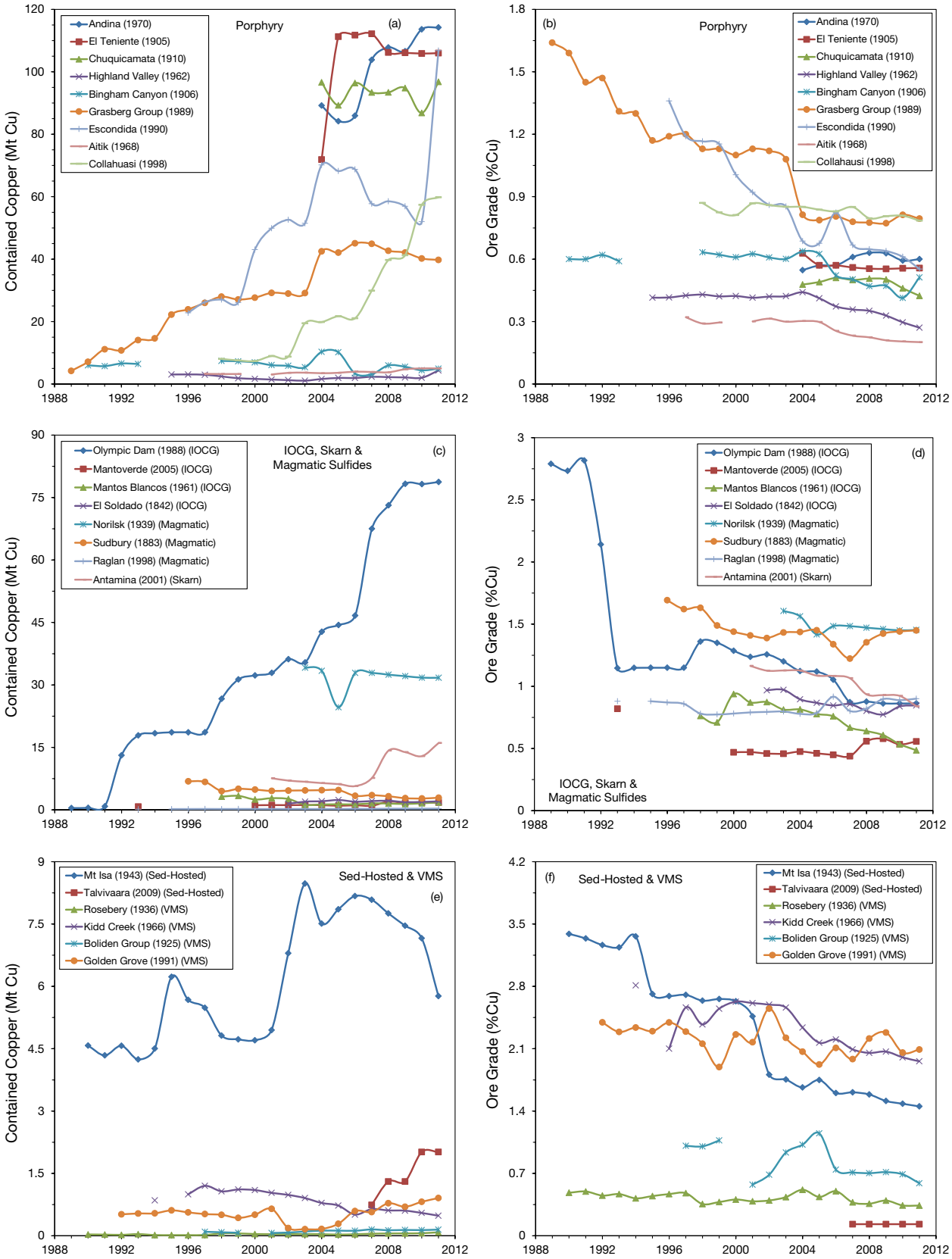


FIG. 5. Selected major Cu projects: contained Cu by deposit type over time (left column), and ore grades by deposit type over time (right column) (year production began in parentheses). Note that for the Grasberg Group, ore reserves only were reported until 2003, with ore reserves and additional mineral resources reported from 2004.

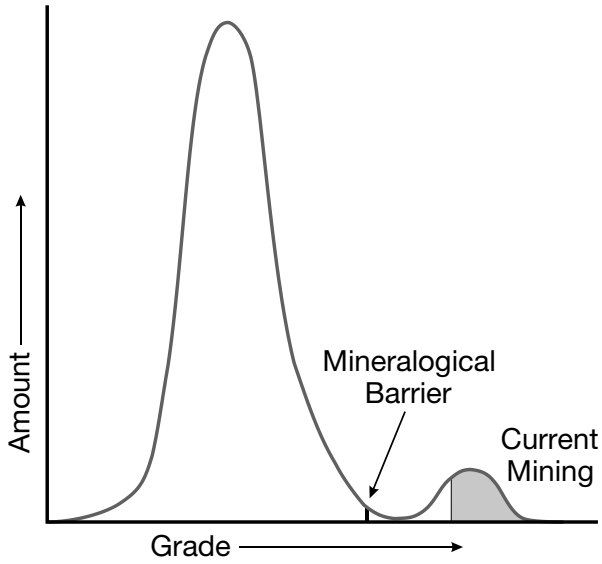


FIG. 6. A conceptual view of grade versus contained metal for geochemically scarce metals, current mining, and the "mineralogical barrier" (redrawn from Skinner, 1976).

cycles (Fig. 8). As discussed previously, this is a complex function of growing demand, technological innovation (e.g., froth flotation, solvent extraction-electrowinning, airborne geophysics, etc.), the growing dominance of porphyry deposits (see Gerst, 2008), supply and new mines, and other factors (e.g., Doggett, 2000). Perhaps most critical is the recent trend whereby, due to boom prices of the late 2000s, some aging mines were able to justify large capital reinvestment based on an increased resource modeled on a lower cutoff grade (e.g., Highland Valley).

The overall product of declining cutoff grades and the growing dominance of porphyry deposits is long-term declines in the average grades of processed ore. The available data for select countries is shown in Figure 9, showing a clear declining trend for most countries. Although Papua New Guinea appears to have stable ore grades, these grades relate to only two large porphyry Cu mines at Ok Tedi and Bougainville. The high Cu ore grades for Australia in the mid-1800s were due to exploitation of near-surface oxide ore (e.g., Peak Downs, Burra Burra), with the depletion of these deposits by the 1890s leading to the exploitation of lower-grade but larger sulfide mineral resources (e.g., Moonta-Wallaroo, Mt. Lyell, Mt. Morgan, Cobar). The rise and fall of Australian ore grades throughout the 20th century is due to the opening of new high-grade mines (e.g., Mt. Isa Cu in 1953, Olympic Dam in 1988, Nifty in 1993) and several low- to medium-grade mines in the 1990s and 2000s (e.g., Northparkes in 1996, Ernest Henry in 1997, Cadia in 1998, Telfer and Boddington redevelopments in 2005 and 2009, respectively). Based on current Australian Cu resources, it is highly unlikely that average ore grades will ever increase, and they look set to gradually decline in the future, albeit at a slower rate than the past. Australian mining history shows the importance of varying ore types and projects in operation, and is mirrored in Canadian Cu mining history (e.g., balance of Sudbury-derived Cu versus Cu/Cu-Au porphyry and Cu-Zn VMS projects).

Another important point is that there are known Cu resources that are not recoverable, often due to policies excluding mining from high conservation value lands or social concerns or opposition. For example, the Windy Craggy Cu deposit in British Columbia, Canada, despite being the largest VMS deposit discovered,[2] is now inside the world heritage-listed Tatshenshini-Alsek Park and cannot be developed (see Laznicka, 2010). Another major Cu-Au project was also

[2] Windy Craggy was estimated to hold 297 Mt at 1.38% Cu, 0.08% Co, and ~2 g/t Au containing ~4.1 Mt Cu, 240 kt Co, and ~600 t Au (Peter and Scott, 1999). This resource would be listed first in Table 6.

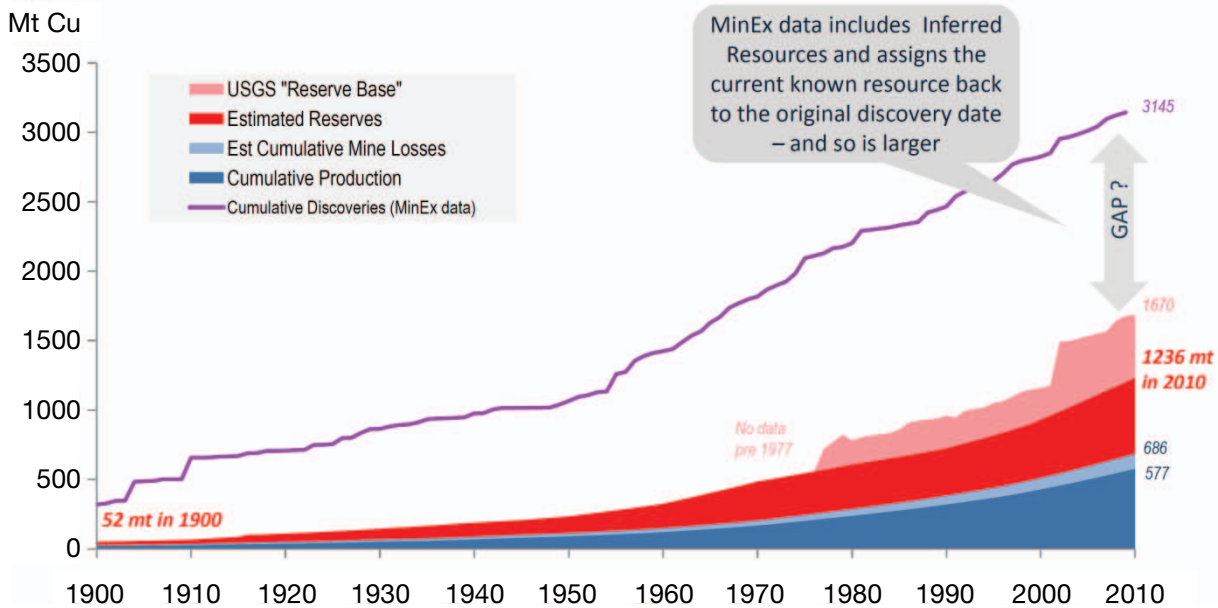


FIG. 7. Global Cu resources over time (Schodde, 2010); note that this graph assumes 20 Mt Cu global production prior to 1900 and that mining recovers 85% of Cu in ore.

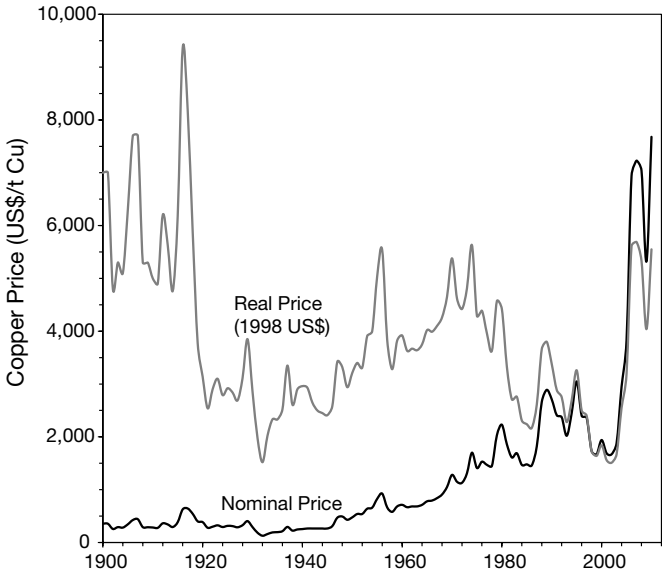


FIG. 8. World Cu prices over time, including nominal (price of the day) and adjusted real prices to 1998 US$ (adapted from Kelly and Matos, 2012).

denied approval by the BC and Canadian governments at Kemess North in 2007, primarily due to concerns over potential impacts on sacred sites from indigenous people. Alternatively, the giant Pebble Cu-Au project in Alaska, United States, faces significant hurdles with respect to complex environmental and social issues (e.g., the region is a rich salmon breeding ground and is renowned for commercial and tourist fishing, which both provide a backbone to local economic and social activity), and it remains unclear whether all necessary approvals for its development will be successfully obtained.[3] The Reko Diq project in Pakistan, in stark contrast, faces ongoing delays due to concerns over social stability (including governance issues) and security in the region, as it is in the very northwest corner of Pakistan and adjacent to Afghanistan and Iran.

In addition, mine waste management will continue to be a growing issue for the Cu sector, especially in light of declining ore grades and the increasing scale of open-cut mines and associated waste rock. The Ok Tedi and Grasberg Cu-Au mines use riverine tailings disposal (~20 and ~80 Mt/year, respectively) and allow extensive erosion of waste rock to rivers (up to ~25 and ~250 Mt/year, respectively), both of which can cause extensive environmental and social impacts (e.g., Paull et al., 2006; Bolton, 2008), while all other Cu mines build and manage tailings dams that will ultimately contain up to billions of tonnes of tailings. In Chile, all tailings dams need to meet a range of stringent engineering criteria, especially regarding earthquake risks. Any tailings or waste rock that contain reactive sulfides present a major risk of acid and metalliferous drainage (due to oxidation), and this problem is growing across the mining industry (see Lottermoser, 2010; Mudd, 2010a). Concern over long-term environmental risks from mine wastes is commonly a major, if not the dominant, factor in community concern and opposition to some Cu projects (e.g., Windy Craggy, Pebble).

[3] For example, type "Pebble copper-gold project" into an internet search and observe the controversy.

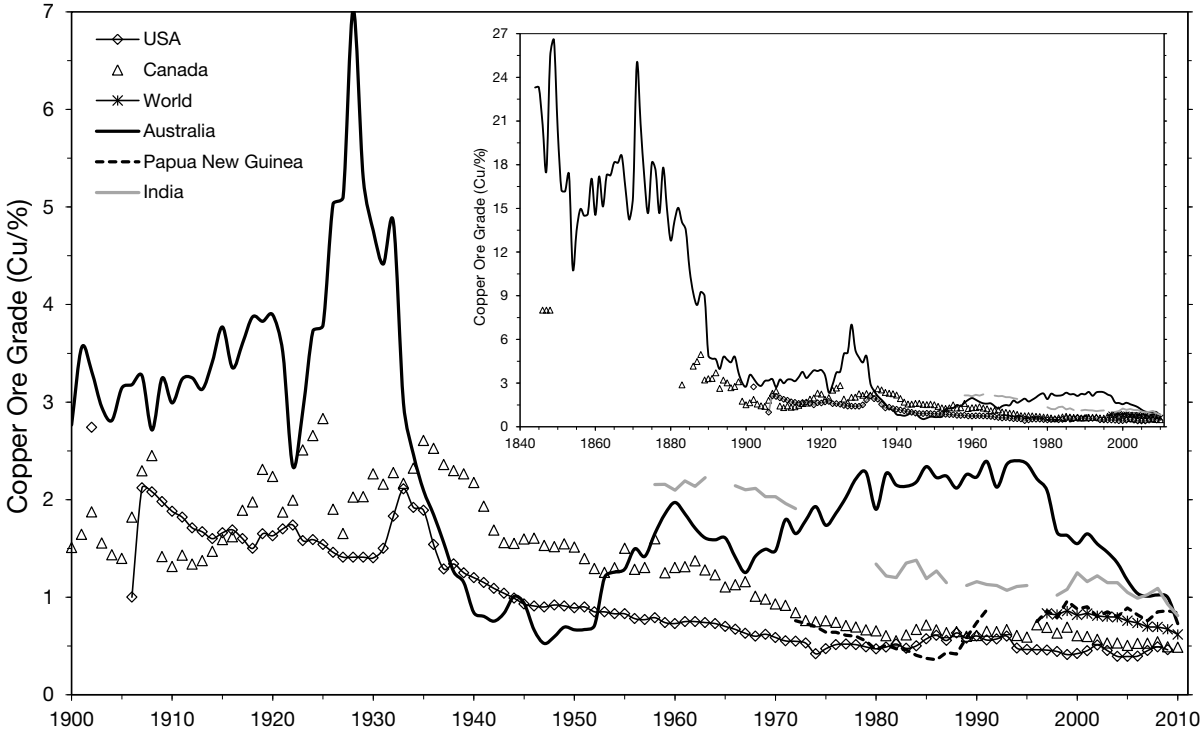


FIG. 9. Country average ore grades of milled ore for select countries over time (Mudd and Weng, 2012; India data added from Indian Bureau of Mines, 1958–2010); note that the world data covers between 70 and 80% of global mine production.

As world progress on greenhouse gas emissions and climate change policy continues to evolve, there may be some projects that, for example, by reliance on emission-intensive coal-based electricity, may be uneconomic when carbon pricing is factored in. Clearly, there are a range of complex sociopolitical, environmental, and economic factors that may act against some Cu resources ever being developed.

Finally, 2010 world Cu production was ~16 Mt Cu (USGS, 1996–2011). If one applies a linear trend line (a conservative option[4]) for world production from 1950 to 2010 (the period of major global industrial growth), a regression with a coefficient of determination of 95.5% can be obtained (Fig. 10). Projecting this model to 2100 gives annual production in the year 2100 of 34.2 Mt Cu, with cumulative production from 2011 to 2100 of 2,214.4 Mt Cu—very close to Schodde's current estimate of global Cu resources. This model is not intended to be a detailed projection of future Cu production, but rather a basic test of likely cumulative production versus economic Cu resources, showing sufficient resources for some decades at least.

Overall, it is clear that there are abundant Cu resources already identified which can meet growing global demands for some decades to come; the primary factors that govern whether a given project is developed will be social, economic, and environmental in nature—certainly not whether there is sufficient Cu known in mineral resources to meet demand.

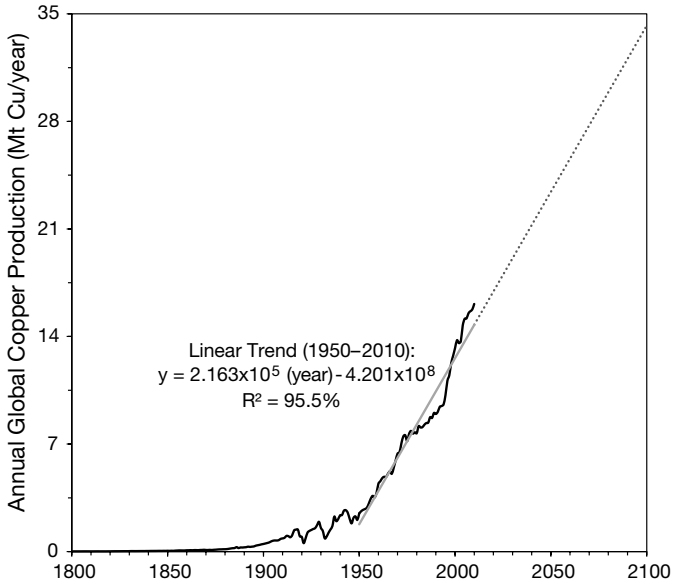


FIG. 10. Variation in world Cu production over time with a linear regression model (1950–2010 only) extrapolated to 2100.

Conclusion

The extent of presently known global Cu resources for the year 2010 has been assessed and analyzed in detail in this paper, including a comprehensive data set on reported mineral resources containing Cu by individual project and deposit type. Our data show that there is at least 1,780.9 Mt Cu contained within a total of 730 projects, with a further 80.4 Mt Cu in China, as well as other projects with resources that may not have been reported. Significantly, our detailed compilation of reported mining company data demonstrates substantial growth in cumulative production and resources, markedly exceeding the previous estimate by Singer (1995). When comparing our 2010 data against trends over time, it is apparent that global Cu resources continue to grow steadily. Some of the key trends that underpin growing Cu resources include technological innovation, growing demand, and declining mining costs, all leading to lowering cutoff grades and declining ore grades. In terms of deposit types, our data show that the majority of total Cu resource is associated with porphyry-type mineralization, especially in Chile, primarily due to the large tonnage and low- to medium-grade nature of these deposits; as such, porphyry deposits contain some 10 times more Cu than any other deposit type. In considering the current known Cu resources and trends, it is clear that copper is far from a peak in known resources or production, with a range of complex social, environmental, and economic factors likely to govern individual projects and whether they are developed (or not).

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[4] Although exponential or power regressions of all historical production data give R^2 values of 99.06% and 99.13%, respectively, they predict annual production in 2100 of 660.9 and 483.4 Mt Cu/year, respectively—clearly unrealistic values. Alternatively, a linear regression model of production from 1992 to 2010 gives an R^2 value of 96.7% and 2100 annual production of 53 Mt Cu/year. Hence, the linear model of 1950 to 2010 data is clearly a more reasonable basis for future projections. A different approach would be to project world population and demand per person, although this would still give estimates in the range of 30 to 50 Mt Cu/year by 2100 (see data in Australian Bureau of Agricultural and Resource Economics, 1995–2010, or Kelly and Matos, 2012). As such, these projections should be considered very approximate only, but they remain a useful conceptual guide.

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APPENDIX 1
Copper Deposit Types

In this section, we summarize the main deposit types, the genetic linkages between these deposit types, and the processes whereby these types of deposits are formed. Although copper resources are also reported for some other deposit types, these are not covered in detail, given either the restricted number of deposits of that type (e.g., the Phalaborwa carbonatite deposit) or the low total amount of Cu contained within a given deposit type (e.g., orogenic and intrusion-related Au-dominated deposits, with <2 Mt contained Cu over 12 projects, compared to our global resource of ~1,780 Mt contained Cu for all deposit types; see previous discussion for more detail).

Magmatic sulfide

Magmatic sulfide deposits form by the segregation of an immiscible sulfide liquid from a mafic or ultramafic silicate magma, with chalcophile elements, such as Ni-Cu-PGEs, preferentially partitioning into the sulfide liquid (Naldrett, 2004). The dominant commodities within magmatic sulfide deposits are Ni, Cu, and the PGEs, in addition to Co, Au, and, more rarely, Ag, Te, and Se. Magmatic Ni-Cu-PGE deposits fall into two broad categories: Ni-Cu deposits, which tend to be sulfur rich and where the PGEs are a by-product only, here termed Ni-Cu-(PGE) deposits; and sulfur-poor PGE deposits, where by-product Ni and Cu may be important. It should be noted that there is some overlap between these two broad groups and some mineral deposits could be classified as both Ni-Cu-(PGE) and PGE deposits. Ni-Cu-(PGE) deposits can be separated into several different classes, according to the type of magmatism that generated the deposit and the age at which the deposit formed (e.g., Archean vs. Proterozoic komatiites), while PGE deposits can be broadly split into three types of mineralization (Naldrett, 2004). These are reef or stratiform mineralization in well-layered mafic/ultramafic intrusions, for example, the Merensky and UG-2 reefs of the Bushveld Complex in South Africa; strata-bound contact-type mineralization such as the Platreef deposits in the Bushveld Complex; and magmatic breccia-type deposits in stock-like or layered mafic/ultramafic intrusions, such as the Lac des Iles deposit in Ontario (Naldrett, 2004). Magmatic deposits can form in a wide variety of settings and are found throughout the majority of the geologic timescale, although clusters of deposits are found around certain ages (e.g., komatiite and komatiitic basalt-associated Ni-Cu-(PGE) mineralization around 2.7 Ga and 1.9 Ga; Naldrett, 2010).

Porphyry

Porphyry Cu deposits are usually large-tonnage, low- to medium-grade mineral deposits genetically linked with porphyry intrusive bodies (e.g., Kirkham, 1971; Sinclair, 2007; Sillitoe, 2010), and are the world's most important source of Cu (Gerst, 2008). They are often associated with other mineral deposit types, such as epithermal, skarn, and manto mineralization (e.g., Hedenquist et al., 1998; Sinclair, 2007; Sillitoe, 2010), and a single mine or mining camp may exploit multiple individual but cogenetic mineral deposit types. They are most often found associated with felsic to intermediate calc-alkaline magmatism within arcs that form above active subduction zones associated with convergent plate margins, such as the present-day Andean magmatic system (Sillitoe, 1972; Richards, 2003; Sinclair, 2007). Porphyry systems can contain a diverse range of commodities, including Cu, Mo, Au, Ag, Re, PGE, W, Sn, Bi, Zn, In, and Pb (Kirkham and Sinclair, 1995). Primary sulfide mineralization within porphyry systems is formed by ore elements preferentially partitioning into an exsolved aqueous hydrothermal fluid that is the source of mineralization (e.g., Candela and Holland, 1986).

Skarn

Skarn deposits generally form during interaction between wall rocks and magmatohydrothermal fluids derived from plutons and associated deeper magma chamber systems (Einaudi et al., 1981; Meinert et al., 2005). They can form during regional or contact metamorphism and by a variety of differing metasomatic processes that can involve a variety of fluids of metamorphic, magmatic, marine, and meteoric derivation (Meinert, 1992; Meinert et al., 2005). Skarns are commonly associated with, and can form adjacent to or even within magmatic plutons and, as such, may be genetically related to porphyry and epithermal deposits, with the majority of skarns found in rock types that originally contained some limestone (Meinert et al., 2005). Skarns can contain a wide range of commodities, including W, Sn, Mo, Cu, Fe, Pb, Zn, Au, Ag, Bi, Te, and As, depending on differences in composition, oxidation state, and metallogenic affinity of the pluton (e.g., Einaudi et al., 1981). Ore minerals can form during both prograde (usually W and Sn oxide mineralization) and retrograde (usually sulfide mineralization) stages of skarn development (Einaudi et al., 1981; Meinert et al., 2005), with precipitation thought to be induced by decreasing temperatures of the ore fluids, fluid mixing, or neutralization of the ore fluid during reaction with wall-rock rock types (Einaudi et al., 1981; Meinert, 1992).

IOCG

The iron oxide copper-gold (IOCG) deposit category was initially defined after discovery of the giant Olympic Dam Cu-U-Au-Ag deposit, but has grown to cover a broad range of somewhat loosely grouped mineral deposit types (e.g., Groves et al., 2010). IOCG deposits, in a strict sense (Groves et al., 2010), are structurally controlled magmatohydrothermal mineral deposits that contain economic abundances of Au and Cu, are LREE enriched, are commonly brecciated, are associated with Na-Ca alteration, and have high abundances of low-Ti Fe oxides that are associated with low-S sulfide mineralization. These IOCG deposits (sensu stricto) also have a temporal, but potentially not spatial, relationship with major magmatic activity and subalkaline to alkaline pluton emplacement (Groves et al., 2010). A range of commodities are present within IOCG deposits, including Fe, Cu, and Au, but often with significant or by-product Ag, U, REEs, Bi, Co, Nb, and P, among others (e.g., Corriveau, 2007). In this study, we attempted to separate other deposits that were previously

classified as IOCG deposits into other categories where suitable and where information allows, with the intention that, within this paper, an IOCG classification refers to the strict definition of Groves et al. (2010). However, it must be noted that in some cases, where information on a deposit is restricted, or where a mining or exploration company has used a sensu lato IOCG classification, a few minor IOCG deposits within our database could actually be skarns or carbonatite-related deposits.

Epithermal

Epithermal mineral deposits form from generally subaerial hydrothermal systems driven by magmatic heat sources, with mineralization occurring at temperatures <300°C and up to 1.5 km below the water table (Simmons et al., 2005; Tosdal et al., 2009). They form in the shallow parts of hydrothermal systems that characteristically develop in volcanic arc settings (Simmons et al., 2005) and may be related to deeper, cogenetic porphyry and skarn systems (e.g., Far East-Lepanto; Hedenquist et al., 1998). Given this, a wide range of commodities are found in epithermal deposits, most commonly Au and Ag, but epithermal deposits may also contain Cu, Pb, Zn, As, Sb, and Sn (Simmons et al., 2005). Epithermal deposits can be broadly split into low, intermediate, and high sulfidation types according to the oxidation state of sulfur in the ore fluid, which also reflects the pH of the system (Hedenquist et al., 2000), although a second classification using characteristic hypogene alteration assemblages is also widely used (Simmons et al., 2005). Where possible, we use the former classification given its prevalence of use in the mining industry.

Volcanogenic massive sulfide

Volcanogenic massive sulfide (VMS) or volcanic-hosted massive sulfide (VHMS) deposits generally occur at or near the seafloor in submarine volcanic environments (Galley and Koski, 1999). They occur in a wide variety of settings and throughout all periods of geologic history, from the Archean (e.g., deposits in the Slave and Abitibi-Superior provinces in Canada; Barrie et al., 1999) to the modern day (e.g., the Solwara-1 and -2 deposits in deep seawater in Papua New Guinea). They are globally distributed and range in size from insignificant to giant, with world-class deposits such as Kidd Creek, Ontario (current resources of 27.4 Mt ore grading 0.16% Pb, 5.06% Zn, 2.00% Cu, and 57.2 g/t Ag, with past production of 145 Mt ore grading ~0.2% Pb, 6.13% Zn, 2.31% Cu, and ~80 g/t Ag), and Windy Craggy, British Columbia (297.4 Mt at 1.38% Cu, 4 g/t Ag, and 0.2 g/t Au; Galley et al., 2007). VMS deposits develop either by the accumulation of sulfide mounds or replacive mineralization during venting of hydrothermal fluids at or near the seafloor. These systems are analogous to black smokers on the modern-day seafloor, and involve precipitation of massive sulfides during venting and interaction of hydrothermal fluids with cold seawater, or during cooling by a combination of the steep near-surface thermal gradient and mixing with seawater-saturated units close to the seafloor (Galley et al., 2007). High-temperature vent fluids are produced by a hydrothermal system driven by underlying heat sources, such as magma chambers associated with oceanic spreading centers (Galley, 1993; Galley et al., 2007). This drives convective circulation, with seawater flowing down from the seafloor to close to the heat source, stripping metals from the lower parts of the crust (Richardson et al., 1987; Jowitt et al., 2012) and transporting them back to the surface (Galley, 1993; Galley et al., 2007). A wide range of commodities are present within VMS deposits, most importantly Cu, Zn, Pb, Au, and Ag, but often with other significant by-products, including but not limited to Bi, Cd, Co, Ga, Ge, In, Mn, Se, Sn, and Te (Galley et al., 2007).

Sediment-hosted Pb-Zn deposits

Sediment-hosted Pb-Zn deposits are mineral deposits where (1) the main economic commodities are Pb and/or Zn, (2) the deposits are sediment-hosted, and (3) in the vast majority of cases, the genesis of the orebody has no direct relationship to igneous activity (Leach et al., 2005). In the majority of cases, these deposits can be split further into sedimentary exhalative (sedex) deposits or Mississippi Valley-type (MVT) deposits, although a number of other, subsidiary classifications, such as Irish type, Broken Hill type, and carbonate replacement, also exist (Leach et al., 2005, 2010). Given the issues with the nomenclature associated with sediment-hosted Pb-Zn mineralization, as discussed by Leach et al. (2005, 2010), we here split sediment-hosted Pb-Zn deposits, where possible, into sedex and MVT types, using the definitions of Leach et al. (2005) and considering that, for many mineral deposits, little or no information beyond the somewhat limited amount given in technical reports may be available. Broadly speaking, metals in both MVT and sedex systems were precipitated through a variety of processes that include synsedimentary precipitation on the seafloor (primarily sedex deposits), diagenesis, epigenetic replacement, and low-grade metamorphism (Leach et al., 2005, 2010). In terms of commodities, by definition both deposit types are dominated by Pb and Zn, but Ag and Cu can be important, and by-product Mn, Tl, As, Ba, Bi, Ge, Hg, Ni, P, and Sb may all be important in both sedex and MVT deposits (Leach et al., 2005). Compared to MVT deposits, sedex deposits generally contain more Pb, Ag, and Cu, with a factor of three difference in Cu concentration between the sedex and MVT deposits where Cu concentrations are reported; in addition, the median Cu grade of MVT deposits is nearly half that of sedex deposits (Leach et al., 2005).

Sediment-hosted stratiform (or red bed) Cu

Sediment-hosted stratiform, or red bed, copper deposits usually consist of a number of thin, extensive zones of disseminated to veinlet Cu and Cu-Fe sulfides that are generally stratiform in nature (Kirkham, 1989; Hitzman et al., 2005), although roll-front and tabular deposits are also known (e.g., Kirkham, 1989). These types of deposits range in size from small to giant and supergiant deposits (Hitzman et al., 2010), although the latter have so far only been discovered in three areas: the Zambian or Katangan Copperbelt, the Kupferschiefer of central Europe, and the Kodaro-Udokan Basin of Siberia (Hitzman et al., 2005, 2010). These deposits are hosted by various types of sedimentary units, most commonly siliciclastic or dolomitic sediments, and may often occur at the contact between subaerial and marine sedimentary sequences within a sedimentary basin (Hitzman et al., 2005,

2010). In general, Cu is the dominant commodity present within these deposits, although Ag and Co are often present and can be important by-products; lesser Pb, U, Zn, Au, and PGEs may also be present, commonly in subeconomic quantities (Singer, 1995; Hitzman et al., 2005). Sediment-hosted stratiform Cu deposits are thought to form by reduction of oxidized base metal-bearing fluids, by reaction with reductants such as organic matter, existing sulfides, or hydrocarbons within the sediments that host the mineralization, causing sulfides to precipitate out of solution and be deposited within the sediments (Kirkham, 1989; Hitzman et al., 2005).