

Giant Metallic Deposits

Future Sources of Industrial Metals

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2 Data on metallic deposits and magnitude categories: the giant and world class deposits

2.1. Data sources and databases

This book strives to be quantitative. It is based on data from mineral deposits, gathered over a period of 40 years and assembled in an unpublished database called GIANTDEP, in my books (Laznicka, 1985a, 1993, 2004) and in *Data Metallogenica* (Epilogue). The data have limitations, they change (improve) with time, and are only as good as their original sources. Readers familiar with a large volume of literature that quotes numerical data from mineral deposits are aware about the constant change and discrepancies, even in a single multi-authored publication! Data used in this book have been reconciled and edited in a uniform way so that discrepancies have been “smoothed”, but not eliminated.

Numerical data

Not considering geographic coordinates, distances and dimensions (length, width, depth, thickness) of orebodies, the principal numerical units that characterize ore deposits are ore tonnage and average metal(s) grade, also cutoff grade if available (it is rarely quoted in the literature). From this can be calculated the economic content of metals in a deposit. The ideal figures would correspond to proven quantities of metals present in a delineated ore deposit before mining started (i.e. pre-mining reserves) and not subsequently modified afterwards. Orebodies with gradational (assay) boundaries against the host rocks also require information about the cut-off grade, as various cut-offs determine the tonnage of material classified as ore. Although ideal tonnage/grade figures, capable to withstand scrutiny, do exist, the majority of data scattered in the literature, including this book, assume to be close to the ideal figures, but offer no background check. Such data are sometimes known as metal(s) endowment and they could be the quantities of ore or metals actually produced during the lifetime of a presently exhausted mine, past production and remaining reserves, calculated quantities of metals never recovered, and similar. In this book, I have endeavored to build the economic metal(s) tonnage figures in a deposit to the highest,

realistic levels often from fragments of data, with minor gaps filled by estimates. In some cases when making numerical comparisons the minimum assured metal quantities, and the maximum extrapolated or estimated quantities, were used side-by-side as alternatives.

Apart from data variation and uncertainty caused by the dimensional category and complexity of a metal accumulation (read below), the data vary by representing either production (cumulative to date or for a period of time only), reserves or resources. The resource figures are always greater (and less certain) than reserve figures. There are several categories of reserves and resources in international use of which two: the “western” ones (defined by the U.S. Geological Survey and used, with modification, by the “western” mining industry) and the “eastern” ones (developed in the former Soviet Union and used in the socialist and some third world countries), have been most widely used.

Cumulative metal tonnage/grade figures recorded during the lifetime of a past producer and from unmined orebodies for which reserve figures have been calculated, are generally final and do not change with time. Figures from operating mines and from prospects undergoing active exploration do change: they mostly grow. Sometimes the growth is phenomenal and figures quoted in the review and reference literature lag behind. The Mount Leyshon low-grade gold stockwork in Queensland went into production in 1986, with published reserves of 23.1 t Au, to deliver more than 3 million ounces (93.3 t) Au by the time of mine closure and rehabilitation in 2002 (Teale and Lynch, 2004).

The copper endowment of the huge El Teniente copper deposit in central Chile has gone from 3 Mt Cu quoted in the pre-1940 literature through 6 Mt Cu in 1960, 9.6 Mt Cu in 1975 (Camus, 1975) to 50 Mt in 1980, 55 Mt in 1996, to the latest figure of 98 Mt Cu. The resource figures for Olympic Dam, quoted in the literature, have increased by a factor of 3.5 between 2004 and 2009, to the present 9.08 billion tons of ore and 79 Mt Cu. There are two reasons for the discrepancy: (1) continuous production and exploration that result in a steady increase of metal produced and proven; (2) the nature of quoted figures. Whereas many of the pre-1960 figures represented production to date, the

more recent figures incorporate past production and resources that include a much lower grade material than what was the case in the past (average grade of 0.63% Cu for the 2009 El Teniente tonnage versus about 2% Cu for the “classical” ore). Unfortunately, the nature of the tonnage/grade data available for the bulk of the world deposits is not always available so what we have are generic figures of variable accuracy. Continuous refinement of mineral databases is thus essential, but in the meantime we have to use data far from perfect to reach quantitative conclusions, as in this book. The novice reader, in particular, has to realize that numbers, as in the tonnage/grade figures, only appear accurate but in many cases they are not.

Data sources

With very few exceptions the ore/metals tonnage and grade figures represent delineated metal accumulations of actual or potentially economic interest. Delineation (that is, exact establishment of limits of an orebody) is essential, as it marks the boundary between the “ore” and the “normal rock”. There is no controversy when there is a sharp drop in metal concentration between the ore and the “rock”, but orebodies with gradational boundaries often change shape and dimension as the cut-off grade (the minimum grade mined) changes with economic conditions. Some obvious and well-known metal accumulations are not presently delineated, hence they are usually not included in mineral deposit databases and compared with the “classical” deposits: they are open-ended. Perhaps the best known example of non-delineated orebodies are the seafloor fields of Fe–Mn nodules. Others are massifs, zones or continuous units of rocks from which metals could be extracted (e.g. serpentinite as a source of Mg, Cr and Ni; anorthosite or nepheline syenite as a source of Al; beach or dune sands for heavy minerals), of which only portions have been delimited as economic orebodies, mostly on property ownership, politico-technologic or environmental grounds.

Tonnage/grade data for delimited classical deposits come from published literature like international research journals (Economic Geology, Mineralium Deposita, Ore Geology Reviews); trade journals (Mining Journal; Engineering and Mining Journal; CIM Bulletin); government publications (U.S. Geological Survey Professional Papers, Bulletins and Mineral Yearbooks; COMRATE, 1975, report); compilations of ore deposit models (Cox and Singer, eds, 1986; du Bray, ed, 1995; Kuznetsov, ed, 1983; Roberts and Sheahan, eds,

1988; Kirkham et al., eds, 1993); conference and symposia volumes; annual reports of publicly listed corporations; and others. The pervasive discrepancy in quoted ore/metal tonnage and grade figures already mentioned above, is frustrating. It is caused by mixing figures for production, reserves and resources current in various times, without indicating the nature of data. Data in text- and reference books retain validity for the traditional deposits, but become rapidly outdated where they deal with recent discoveries and actively explored properties. Increasingly, last minute tonnage/grade data are posted at company web pages. Reassembled data can be found in numerous databases, manual and electronic (e.g. CRIB, subsequently MRDS of the U.S. Geological Survey, Mason and Arndt, 1996; LODE database of large European deposits; GEODE), but not many are publicly available, at least not for an affordable cost.

The “mainstream data” published in and by organizations domiciled in the developed English-speaking countries (the United States, Canada, Australia, South Africa) are most abundant, accessible and consistent. They have a hundred year long tradition. Information from countries that publish in major European languages is less consistent, scattered and often hard to reach outside the countries of origin, but it does exist and circulate at least in compilations. Data in the literature printed in Cyrillic (former USSR, Bulgaria, Serbia, Mongolia) and especially in Asian and Arabic scripts, can be read by few, so only English translations or review articles circulate widely and enter the Western awareness. The traditional Anglophone disinterest about the literature outside the mainstream has been further compounded by foreign governments’ secretiveness and censorship, prevalent especially in the literature from communist and socialist countries between about 1940 and 1990 (compare Laznicka, 1985b). In the past ten years or so, with globalization and international investments booming, a wealth of tonnage/grade data has been seeping out of the former Soviet Union, China, Eastern Europe, Mongolia and Vietnam, leaving North Korea as the last remaining no-data recluse. Capture and utilization of such data, however, still remains incomplete.

GIANTDEP database: This database supports the numerical conclusions reached in this book. The database is continuously evolving, hence the conclusions change slightly with time. This book presents conclusions based on the 1997–1998 state

of GIANTDEP and published in Laznicka (1999), as well as conclusions based on the most recent, 2008–2009 GIANTDEP 4 version. In this database each entry represents an exceptional accumulation of one ore metal only in an orebody, ore deposit, ore field, district or basin, identified as a locality (the internal complexity and dimensions of the various types of “localities” are reviewed below). In most cases there is one database entry per locality (for

example, the giant Kirkland Lake gold ore zone in Ontario is a single entry locality, as only gold is accumulated above the giant deposit threshold). When one locality stores exceptional tonnages of more than one metal, it is entered two or more times (Table 2.1).

Table 2.1. Deposits and districts with exceptional accumulations of two or more metals; updated from Laznicka (1999)

Metals	Number of localities	Example locality	Metals	Number of localities	Example locality
2 metals			3 metals		
Au, Ag	1	Pachuca, Mexico	Ag, Pb, Zn	6	Sullivan, Canada
Ag, Cu	2	Lubin (Kupferschiefer), Poland	Ag, Pb, Au	1	Beregovo, Ukraine
Ag, Pb	6	Santa Eulalia, Mexico	Ag, Cu, Mo	1	Butte, Montana, U.S.A.
Ag, Sn	3	Potosi, Bolivia	Ag, Cu, Zn	1	Kidd Creek, Canada
Ag, Zn	1	Rajpura-Dariba, India	Au, Cu, Mo	2	Petaquilla, Panama
As, V	1	Kerch Fe Basin, Ukraine	Bi, Sn, W	1	Shizhouyuan, China
Au, As	2	Vasil’kovskoye, Kazakhstan	Cu, As, Se	1	Rio Tinto ore field, Spain
Au, Cu	13	Grasberg, Indonesia	Cu, Ni, PGE	2	Sudbury Complex, Ontario ¹⁾
Au, Te	2	Cripple Creek, Colorado, U.S.A.	Au, U	1	Witwatersrand, S. Africa ¹⁾
Pb, Cd, As	1	Tsumeb, Namibia			
Bi, Sn	1	Gejiu, China	PGE, Ni, Au	2	Merensky Reef, South Africa
Cr, PGE	2	Great Dyke, Zimbabwe ¹⁾	Ti, Fe, V	1	Bushveld Magnetite, S. Africa
Cu, Mo	10	Chuquibambilla, Chile	W, Bi, Te	1	Verkhnyye Qairakty, Kaz.
Cu, Co	1	Katanga (Shaba) Copperbelt	Zr, Nb, REE	1	Ilímaussaq, Greenland ¹⁾
Cu, Ni	2	Jinchuan, China			
Fe, Mn	1	Urucúm (Corumbá), Brazil	4 metals		
Fe, V	1	Bakchar ore field, Russia	Cu,U,Au,Ag	1	Olympic Dam, South Australia
Mo, U	1	Billingen (Alum Shale), Sweden	Ag, Mo, Cu, Au	1	Bingham porphyry, U.S.A.
Nb, REE	1	Bayan Obo, China	Pb, Zn, Ag, Cu	1	Mount Isa, Australia
Nb, Th	1	Araxá, Brazil	Zn, Pb, Ag, Bi	1	Brunswick # 6, 12; Canada
Nb, Zr	1	Lovozero Complex, Russia ¹⁾	REE, Y, Nb, Sc	1	Tomtor, Anabar Massif, Russia
Ni, Co	1	New Caledonia laterites			
Pb, Sb	1	Bawdwin, Myanmar (Burma)	5 metals		
Pb, Zn	8	Century, Australia	Zn, Pb, Ag, As, Sb	1	Cerro de Pasco, Peru
			Cu,U,Au,Ag,REE	1	Olympic Dam

¹⁾ Cumulative tonnage of several deposits in a mineralized complex

The number of entries in GIANTDEP is thus larger than the number of localities. The huge Olympic Dam deposit in South Australia is an example of a five-metals “supergiant” reported to contain, in the 2009 global resource of 9.08 billion tons, 79 mt Cu @ 0.87%, 2906 t Au @ 0.32 g/t, 1.96 mt U @ 0.0216% and 15620 t Ag @ 1.5 g/t (BHP Billiton, 2009). Two additional metals: Fe (3 bt @ 30%) and Ce–La rare earths (~45 mt @ 0.5%) are not recovered, and Fe is below the giant threshold (it is a “large” metal accumulation). The total calculated value of the contained metals, at average prices, is of the order of US\$ 400 billion, although not all the metals are recoverable. Olympic Dam is the single

largest U deposit, and fourth largest Cu deposit, in the world and the largest Au, U and Cu resource in Australia.

Most localities in the GIANTDEP file are single deposits or sometimes composite entities (ore fields, districts, ore zones, belts and systems), the metal content of which is a sum of metals in several orebodies or deposits that, individually, are not of the “giant” magnitude. A minority of localities are members of hierarchically arranged sets in which the lower rank metal accumulations (orebodies, ore deposits) are included in higher rank groupings like ore fields, districts or basins. Witwatersrand is a typical example: it is a “basin” (i.e. the first-order

division) subdivided into several goldfields (second-order division, e.g. West Wits), some of which contain still lesser, third-order divisions such as individual “reefs” (=orebodies like Vaal Reef). The locality rank is clearly listed in GIANTDEP and further discussed below.

Also included in the database are several deposits undergoing active exploration where the early results (drill intersections) suggest the “giant” magnitude, but without tonnage figures published yet. The Boyongan deposit in the Philippines, with 0.8% Cu and 1.9 g/t Au in a 366 m long drill interval, is an example. Also included are several deposits of presumably exceptional size (“superlarge”, “supergiant”) especially in Russia and China, for which no figures are available.

2.2. Giant and world class ore deposits: definition and characteristics

Concept history

Metallic ore deposits and districts have been known and exploited since antiquity and their number steadily grew. As, before the Industrial Revolution, only ten metals had been known and utilized (gold, copper, tin, iron, lead, silver, mercury, antimony, arsenic, bismuth, partly zinc for alloys) the number of mines and their geological variety had been small. Some ancient deposits or mines were famous because of the contribution they made to the wealth and power of the local state, territory or royalty, and/or because of their importance for the economy and trade of the medieval and earlier world. Selection of the famous mines of antiquity and of medieval times include Sar Chesmeh, Iran; Queen Sheba gold mine in Yemen; the King Solomon copper mines near Timna, Israel; the Laurium (Lavriion) silver mines in Greece, the principal wealth source of the Athens state; the Mahd-adh-Dhahab gold mine in Arabia; the Kolkhida gold area in the Caucasus; the Transylvania gold region (Roşia Montană, Brad) in Romania; the Cornish tinfield in Great Britain; the Erzgebirge tin and silver region (Freiberg, Schneeberg, Jáchymov, Cínovec); the Kutná Hora silver mines in Bohemia; the silver mines of the Spanish Meseta and Almadén mercury deposit; and many others.

In the old days mineral deposits were neither systematically explored and their reserves calculated and published, nor were there systematic and reliable records of cumulative metal production,

hence quantification was impossible. In retrospect we now know that the Queen Sheba and King Solomon mines were small deposits; Lavriion, Kutná Hora, Jáchymov, Freiberg, Mahd adh Dhahab were medium to large deposits; and only Roşia Montană, Almadén, Cornwall and Iberian Meseta as a whole, were giant or world-class deposits as defined below. A large influx of giant deposits followed the conquest of the Americas (e.g. Potosí and Cerro de Pasco in Bolivia and Peru; Guanajuato, Zacatecas and Pachuca in Mexico; Morro Velho in Brazil) and, of course, the Industrial Revolution when the number of industrial metals discovered and later utilized kept rapidly growing. Quantitative data on mineral deposits (grade and tonnage) were, however, entering the literature very slowly and most were incomplete figures for short periods of production. De Launay (1913) and the earlier issues of *Economic Geology* (from 1907 to 1940) quoted quantitative data very sparingly. Ore reserve figures became available relatively late, in the 1930s, pioneered by the data generated in the large, bulk mined porphyry copper deposits of the American West (e.g. Bingham, Morenci) and published mostly in the U.S. Geological Survey Professional Papers and Bulletins. For a brief period of time before World War 2 government agencies in the former USSR (e.g. Ural'skaya Planovaya Komissia, 1934), also published ore reserve figures for the purpose of industrial planning. The latter publications, in Russian, are virtually unknown and unread in the West and, at the onset of World War 2, they were soon terminated and replaced by secrecy in their home country.

It was not until the early 1960s and the onset of computerization when data became sufficiently abundant to construct global databases and perform numerical analyses. Metallogeny, based on geotectonic models of the day (geosynclines & orogenic belts until 1968, plate tectonics afterwards), became popular and its most colorful expression was the early generation of metallogenic maps published between 1955 and 1985 (e.g. Shatalov et al., 1966; Laffitte et al., 1970; Grushevoi et al., 1971; Guild et al., 1981; read Foose and Bryant, 1993, for bibliography). Probably the earliest quantitative map of the world's mineral deposits was published by Laffitte and Rouveyrol (1964, 1965). The magnitude of ore deposits (districts), taken as the percentage of global endowment of each commodity then, was shown by the size of the symbol; for example, of the then 280 million tons of cumulative world copper production and reserves in 116 deposits, 5

deposits contained 38% of the total copper and were shown by large symbols. Most of the largest symbols in Laffitte and Rouveyrol (1964) map corresponded to giant deposits defined below, as known in the 1960s, although some “deposits” were, in fact, large mineralized provinces (e.g. the African Copperbelt, Arizona-New Mexico Cu province). Since the 1960s the number of ore “giants” has almost tripled.

Several quantitative databases of the world’s ore deposits (e.g. MANIFILE, Laznicka, 1973a; CRIB, later renamed MRDS, database of the U.S. Geological Survey, Calkins et al., 1973; U.S. Geological Survey, 1988; Mason and Arndt, 1996) and national/regional ore deposits (e.g. CANMINDEX of Canada, Picklyk et al., 1978; Mindep of British Columbia and Yukon) were initiated in the late 1960s–1970s and some have been later used with geographic information systems (GIS; e.g. Sinclair et al., 1999). The magnitude of ore deposits followed from figures and, more strikingly, from graphic plots. It was thus possible to separate the “exceptional” deposits from the “normal” ones but there was no special terminology for the exceptional deposits and/or a magnitude classification.

Magnitude terminology for deposits of geological resources has been first developed by the petroleum industry (e.g. Klemme et al., 1970) and the United States’ literature uses the following terms applied to quantities of recoverable petroleum in ground (Hobson and Tiratsoo, 1981):

- Significant oilfield 1 million barrels plus
- Major oilfield 25 million barrels plus
- Giant oilfield 100 million barrels plus
- Supergiant oilfield 10 billion barrels plus

A barrel contains 42 U.S. gallons or 159 litres of fluid. The international magnitude limit of giant oilfields is larger than the U.S. counterpart (500 million barrels plus) and there were 187 giant and 17 supergiant oilfields in the world, in the 1970s (Hobson and Tiratsoo, 1981). The above count included 33 giant and supergiant fields and these, although they represented mere 0.1% of the significant and larger petroleum accumulations, held more than a quarter of the estimated ultimately recoverable oil resources of the world.

The Russian book edited by Favorskaya and Tomson (1974) used the designation “krupnye mestorozhdeniya” (=large ore deposits) in its title and is generally considered to be the initiator of selective treatment of only the exceptional ore

deposits. True to the secrecy that applied to grade/tonnage information in the former Soviet Union, the book is non-quantitative. In about the 1980s, the geological and mineral industry jargon has been enriched by inclusion of the highly subjective term “world class deposits” that rapidly infected even the serious and precise research literature and conference proceedings of the 1990s and beyond (e.g. Cox and Singer, 1986; Whiting et al., 1993; Clark, 1995; Keith and Swan, 1996; Naldrett, 1999a). The term seems to be mainly an attention catching and marketing tool and is so relative that it conveys no real information about the magnitude of the deposit and cannot be used for comparison purposes (the “world-classiness” is in the eyes of the beholder). Alternative non-quantified magnitude terms used in the Chinese literature are “large”, “superlarge” as well as “giant” and “supergiant” deposits (e.g. Pei Rongfu, editor, 1997). Russian literature has used, interchangeably, terms like “unique”, “large”, “exceptional” and “giant” (e.g. Litvinenko et al., 1996; Epstein et al., 1994). Because of state censorship and unavailability of production/reserve figures in communist countries until recently, the use of non-quantified magnitude figures had some justification.

Mining operations are characterized and ranked on the basis of ore tonnage and/or production per day, month, year. This is widely used in planning and engineering management but is not of much use in economic geology as a small, high-grade deposit could contain more metal than a large, low-grade deposit. Greatness of a metal accumulation can be further expressed by a magnitude rank based on the tonnage of ore in reserve or, better, by tonnage + grade at a certain cut-off grade. This gives best results when applied to populations of mutually comparable deposits (same metals, same type) like porphyry coppers. Such an information is best displayed in grade/tonnage graphs (e.g. Cox and Singer, eds., 1986).

The remaining quantitative indicator of an orebody greatness is its monetary (usually U.S. dollar) value, applied to the “value” of metal(s) in the economic ore derived by multiplying the tonnage of the contained metal(s) by the present LME price (for example, the Olympic Dam deposit had a value of about \$ 162 billion in the late 1990s). As with the ore tonnages above, dollar values are most helpful when used for comparison of contemporary deposits of the same metals and similar styles.

Several attempts to classify magnitude categories of ore deposits and introduce precise terminology

have been made, since the 1980s, on the basis of (1) share of the known global endowment of a commodity (e.g. copper) held by a deposit (e.g. Singer, 1995), an economic geologic premise; (2) magnitude of ore metal accumulation in relation to the mean crustal content of elements (e.g. Laznicka, 1983b), a geochemical premise; (3) dollar values, an economic premise.

Economic geologic premise: the world class deposits (WCD)

Singer (1995) pointed out that the recently popular term “world class deposit” had been overused and had no frame of reference whatsoever. Using data assembled in the U.S. Geological Survey databases (already applied in preparation of the mineral deposit models and grade/tonnage graphs; Cox and Singer, eds, 1986; du Bray, ed, 1995), he proposed a quantitative definition where WCD’s are those in the “upper 10% of deposits in terms of contained metal”, a magnitude comparable with his alternative term “giant”. A “super-giant” would apply to the upper 1% of deposits. Singer (1995) placed the lower limits of WCD’s of the five metals he processed at 100 t Au, 2,400 t Ag, 2 mt Cu, 1.7 mt Zn, 1.0 mt Pb, hence there is some discrepancy in respect to the “giant” and “super-giant” thresholds proposed by Laznicka (1999) and followed in this book (these are: 250 t Au, 7,000 t Ag, 2.5 mt Cu, 6.7 mt Zn, 1.5 mt Pb).

Singer’s approach requires accurate and finite numbers of deposits together with their grades and tonnages, but there is likely a discrepancy between the numbers of deposits in the USGS databases and the objective reality. The U.S. Geological Survey database used by Singer, for example, included 1,325 Cu deposits whereas in my personal database there are more than 2,000 Cu entries and I am still aware that this number is incomplete. I suspect that the USGS databases become progressively undernourished in ore deposit entries as one moves away from the United States and from countries where the USGS personnel worked as advisers (e.g. the Arabian Peninsula), and that this undernourishment becomes significant in the C.I.S. countries and China. Moreover, Singer (1995) did not carry on his exercise beyond the five metals and as the source database is not available, it is not possible to extend the WCD magnitude terminology to deposits of other metals.

WCD’s are clearly economic geologic, rather than metallogenic, entities so they are influenced by price, demand, markets that do not directly correlate with the geochemical magnitudes of metal

concentration and accumulation on which is based the “giant” deposit terminology pursued here (it is explained below). Singer’s (1995) WCD’s of the “unwanted” (like Th, As) and limited demand (Nb, REE) metals that have few database entries would be hardly comparable with deposits of the eagerly sought metals like Au, Cu, Zn endowed with thousands of deposits each. Given the lack of perfect databases, I suggest to utilize the term “world class” in the subjective, informal and approximate way as is the case with many comparable terms in geosciences and mining. Long et al. (2000) used the term “significant deposit” for those that collectively account for 99% of the past U.S. production and remaining resources of Au, Ag, Cu, Pb and Zn. Alternatively, top ten deposits (rather than top 10% of deposits) of each metal could be declared as of “world class”, and the magnitude of the tenth entry selected as the WCD threshold until a new major discovery is made that would move the threshold one notch up (this has happened since the first edition of this book in 2006, when the threshold was 24 mt Cu). Example: ten largest Cu ore fields and districts (composite localities) ranked by metal endowment:

1. Chuquicamata, 110.5 Mt Cu
2. Lubin (Polish Kupferschiefer), 91 Mt Cu
3. Rio Blanco cluster, 80 Mt Cu
4. Kolwezi ore field, 67 Mt Cu
5. La Escondida ore field, 54 Mt Cu
6. Noril’sk-Talnakh district, 47 Mt Cu
7. Ertsberg-Grasberg ore field, 44 Mt Cu
8. Collahuasi ore field, 40 Mt Cu
9. Dzhezkazgan ore field, 35 Mt Cu
10. Bingham ore field, 34 Mt Cu.

Applied to single deposits (or compact clusters), the ranks will change:

1. El Teniente, 98 Mt Cu
2. Chuquicamata deposit, 85 Mt Cu
3. Olympic Dam, 79 Mt Cu
4. Tenke-Fungurume, 45.6 Mt Cu
5. Butte, 35 Mt Cu
6. La Escondida, 34 Mt Cu
7. Cananea, 30 Mt Cu
8. Bingham Canyon porphyry, 28.5 Mt
9. Morenci, 28 Mt
10. Los Pelambres-Pachon, 27 Mt Cu.

The “world class” threshold thus would be either 34 Mt Cu or 27 Mt Cu, depending on choice.

An alternative to the “world class” characterization of an ore deposit could be the share (percentage) of the world’s endowment of the same metal, a deposit

stores. So the Kalahari Mn Basin stores some 48% of the world's on-land Mn, Olympic Dam is credited with almost 50% of the world's U, Almadén has some 29% of the world's Hg (Fig. 2.1). Surely these figures would vary with various authorities and change with time, but so do all

quantities based on mining data. Laffitte and Rouveyrol (1964) used this approach successfully in constructing what was one of the first quantitative maps of the world's ore deposits (metallic and nonmetallic).

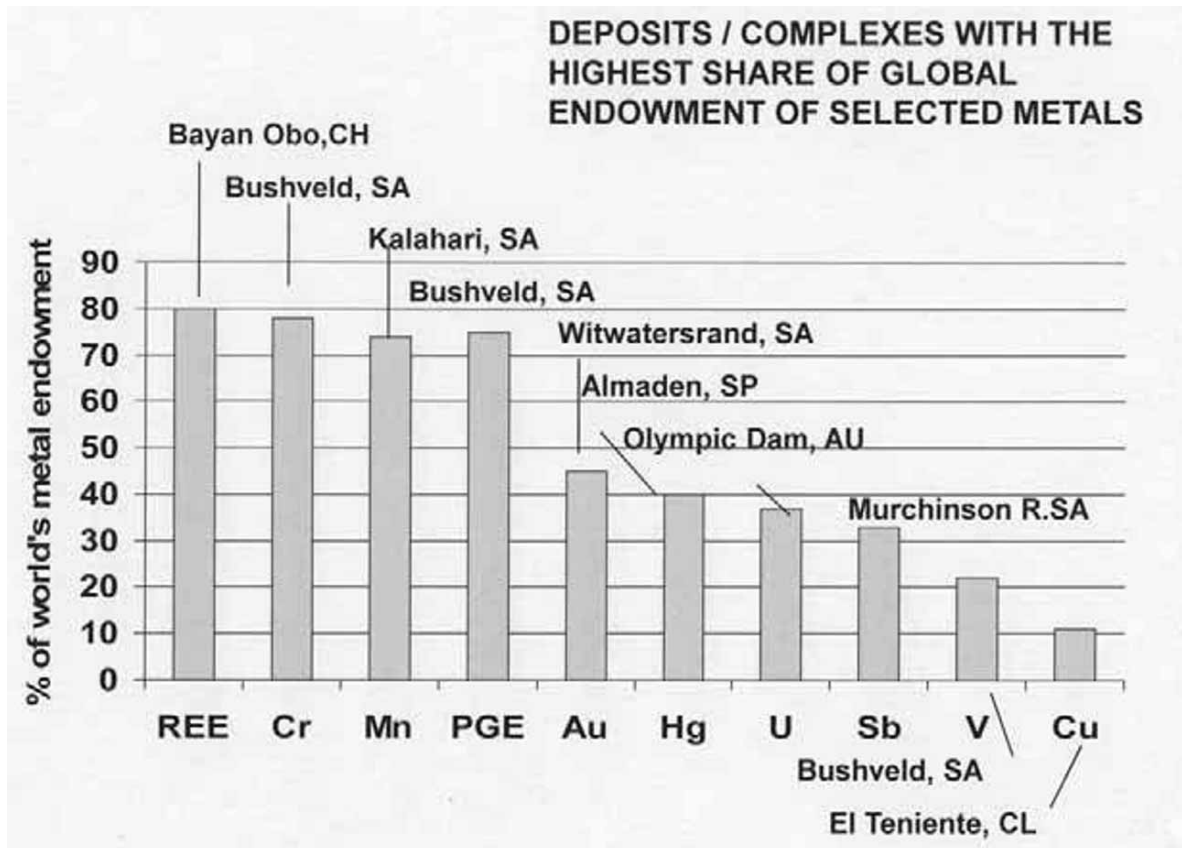


Figure 2.1. The share of individual deposits, districts and complexes of the global endowment of selected metals

The geochemical premise: giant and super-giant deposits

Shortly after first estimates of elements abundances in the crust had been published (Clarke, 1924), it became obvious that metal concentrations in ore deposits are closely related to them. Fersman (1933) coined the term “clarke” as a unit of the mean crust content (for example, clarke of copper was then 30 ppm Cu), as well as the term “clarke of concentration” (CC) alias concentration factor, which is an ore grade divided by clarke. So CC of a 1.0% Cu ore is $10,000 \text{ ppm} / 30 = 333$.

McKelvey (1960) devised a relationship between crustal abundances and potential United States' ore reserves, expressed as $R = A \times 10^{9-10}$, where R=reserve in short tons; A=clarke in percent. In

case of lead, using the Pb clarke of 0.0013%, the U.S. lead resources fell into the range of 1.3–13 million tons (or 1.6–16 million tons if the more commonly quoted Pb clarke of 16 ppm were used). As this was lower than the 1960 reality of 31.8 million tons of lead in the U.S. reserves, Erickson (1973) introduced the factor of 2.54 to modify the McKelvey's formula as $2.54A \times 10^{9-10}$. This was based on the 31.8 mt of Pb resource divided by McKelvey's 13 mt Pb. Erickson (1973) claimed that this formula represented “the potential recoverable resource for most elements”.

Increasing globalization of mineral deposit data, and the realization that metallogeny is really a geochemistry of exceptional metal accumulations, required a common denominator that would make it possible to compare and rank deposits of the

various metals according to the effectiveness (efficacy) of ore forming processes, as well as favorability of settings in which these processes took place plus their preservation history. In simple words, there was a need to compare deposits of metals with highly variable clarke values such as iron, copper, tin, uranium and gold by magnitude of their geochemical accumulation process to assign the top contender the rank of a “geochemical giant”.

Magnitude of metals’ accumulation: This task clearly could not have been accomplished by comparing straight economic tonnages of metals in orebodies, as a 1000 ton gold orebody is clearly more exceptional and it took more effort to form than a 1000 ton deposit of tin, copper or iron. The only means to measure and compare the geochemical effectiveness would be with the help of derived, artificial units, such as tonnages of a hypothetical rock that would accommodate those thousand ton contents of various metals in clarke concentrations. Such a unit is called tonnage accumulation index (tai; Laznicka, 1983b, 1999) and is derived by dividing the economic metal content in a deposit by metal clarke.

After calculating tonnage accumulation indexes for thousands of metallic deposits in a database, several classes of magnitude in terms of metal accumulation effectiveness became apparent. The top ones, with tai’s of the order of $n \times 10^{11}$ and $n \times 10^{12}$, have been named giant and supergiant (Laznicka, 1983, 1999). Magnitude thresholds are different for every metal because every metal has a different clarke, so a giant iron deposit starts at 4.3 billion tons of Fe, a copper giant starts at 2.5 million tons of Cu, a gold giant requires at least 250 t Au. The problem of the enormous range of tonnage magnitudes within one division of a log scale (e.g. between 2.5 and 25 million tons of copper) has been rectified by subdividing each log interval into three equal portions that are referred to as “low”, “mid” and “high”. So a 5 mt Cu deposit would be a “low giant”; a 12 mt Cu deposit would be a “mid giant”; a 20 mt Cu deposit would be a “high giant”. The same applies to subdivisions in the “large” and “supergiant” divisions. Names of the accumulation magnitude divisions follow from Table 2.2; Table 2.3. lists thresholds of magnitude divisions for each metal.

Concentration factor (clarke of concentration): Tonnage accumulation values say nothing about metal concentration although it is assumed that the delimited deposits listed in the literature have sufficient grades to be of economic interest. As

classical ore deposits are also exceptional concentrations of metals expressed in reports as ore grade (in percent, ppm, ounces per ton), a unit of clarke-related concentration is needed to work together with tai. This unit is the already mentioned clarke of concentration, CC (Fersman, 1933) and the proposed terminology of the metal concentration magnitudes follows from Table 2.4.

Table 2.2. Terminology of metal accumulations (deposits, districts) based on tonnage accumulation index (tai), exemplified by Cu (Cu clarke=25 ppm)

Magnitude term	Tai: lower threshold	Corresponding Cu tonnage
Supergiant (deposit)		
high supergiant	6.6×10^{12}	165 mt (unknown)
mid supergiant	3.3×10^{12}	82.5 mt
low supergiant	1×10^{12}	25 mt
Giant (deposit)		
high giant	6.6×10^{11}	16.5 mt
mid giant	3.3×10^{11}	8.25 mt
low giant	1×10^{11}	2.5 mt
Large (deposit)	1×10^{10}	250 kt
Medium (deposit)	1×10^9	25 kt
Small (deposit)	1×10^8	2,500 t
Very small (deposit)	1×10^7	250 t

Clarke-normalized quantitative data from metal deposits have the advantage of being completely devoid of the politico-economic and technological influences, hence any metal accumulation can be accommodated and compared. This makes it possible to maintain continuity in the treatment of both “ores” and “rocks”.

Most giant and supergiant deposits defined by relation to metal clarkes are also the world class deposits of Singer (1995), but there are exceptions. The geochemically most abundant metals Fe, Al and Mg form ore deposits with very low clarkes of concentration (between 3 and 10; in case of Mg recovered from sea water CC is negative, i.e. Mg concentration in seawater is less than Mg clarke), hence an iron deposit needs a resource of at least 4.3 billion tons of Fe to become a “geochemical giant”. Corresponding tonnages for Al are 8 billion tons and for Mg 3.2 billion tons. There are few iron accumulations that qualify (e.g. the Snake River Fe deposit, Yukon, 11.62 bt of Fe), but none of aluminum recovered from bauxite. The largest listed bauxite district, Boké-Gaoual in Guinea, has Al content of 3.88 billion tons, hence it is a “mid-large” accumulation. If, in the future, anorthosite should become an industrial Al ore, many anorthosite massifs will become giant deposits.

Table 2.3. Crustal abundances (clarkes), thresholds and range of the “large”, “giant” and “super-giant” accumulations of metals. Modified from Laznicka (1999)

Metal	Clarke ppm	Large deposits			Giant deposits			Supergiant deposits		
		low	Mid	High	low	Mid	High	low	Mid	High
Al	8.0×10^4	8.0×10^8	3.2×10^9	5.6×10^9	8.0×10^9	3.2×10^{10}	5.6×10^{10}	8.0×10^{10}	3.2×10^{11}	5.6×10^{11}
Fe	4.3×10^4	4.3×10^8	1.7×10^9	3.0×10^9	4.3×10^9	1.7×10^{10}	3.0×10^{10}	4.3×10^{10}	1.7×10^{11}	3.0×10^{11}
Ti	4.0×10^3	4.0×10^7	1.6×10^8	2.8×10^8	4.0×10^8	1.6×10^9	2.8×10^9	4.0×10^9	1.6×10^{10}	2.8×10^{10}
Mn	7.2×10^2	7.2×10^6	2.9×10^7	5.0×10^7	7.2×10^7	2.9×10^8	5.0×10^8	7.2×10^8	2.9×10^9	5.0×10^9
Zr	2.0×10^2	2.0×10^6	8.0×10^6	1.4×10^7	2.0×10^7	8.0×10^7	1.4×10^8	2.0×10^8	8.0×10^8	1.4×10^9
REE	1.5×10^2	1.5×10^6	6.0×10^6	1.1×10^7	1.5×10^7	6.0×10^7	1.1×10^8	1.5×10^8	6.0×10^8	1.1×10^9
Cr	1.3×10^2	1.3×10^6	5.2×10^6	9.1×10^6	1.3×10^7	5.2×10^7	9.1×10^7	1.3×10^8	5.2×10^8	9.1×10^8
V	1.0×10^2	1.0×10^6	4.0×10^6	7.0×10^6	1.0×10^7	4.0×10^7	7.0×10^7	1.0×10^8	4.0×10^8	7.0×10^8
Zn	6.5×10^1	6.5×10^5	2.6×10^6	4.6×10^6	6.5×10^6	2.6×10^7	4.6×10^7	6.5×10^7	2.6×10^8	4.6×10^8
Ni	5.5×10^1	5.5×10^5	2.2×10^6	3.9×10^6	5.5×10^6	2.2×10^7	3.9×10^7	5.5×10^7	2.2×10^8	3.9×10^8
Cu	2.5×10^1	2.5×10^5	1.0×10^6	1.8×10^6	2.5×10^6	1.0×10^7	1.8×10^7	2.5×10^7	1.0×10^8	1.8×10^8
Co	2.4×10^1	2.4×10^5	9.6×10^5	1.7×10^6	2.4×10^6	9.6×10^6	1.7×10^7	2.4×10^7	9.6×10^7	1.7×10^8
Y	2.4×10^1	2.4×10^5	9.6×10^5	1.7×10^6	2.4×10^6	9.6×10^6	1.7×10^7	2.4×10^7	9.6×10^7	1.7×10^8
Nb	1.9×10^1	1.9×10^5	7.6×10^5	1.3×10^6	1.9×10^6	7.6×10^6	1.3×10^7	1.9×10^7	7.6×10^7	1.3×10^8
Li	1.8×10^1	1.8×10^5	7.2×10^5	1.3×10^6	1.8×10^6	7.2×10^6	1.3×10^7	1.8×10^7	7.2×10^7	1.3×10^8
Sc	1.6×10^1	1.6×10^5	6.4×10^5	1.1×10^6	1.6×10^6	6.4×10^6	1.1×10^7	1.6×10^7	6.4×10^7	1.1×10^8
Ga	1.5×10^1	1.5×10^5	6.0×10^5	1.1×10^6	1.5×10^6	6.0×10^6	1.1×10^7	1.5×10^7	6.0×10^7	1.1×10^8
Pb	1.5×10^1	1.5×10^5	6.0×10^5	1.1×10^6	1.5×10^6	6.0×10^6	1.1×10^7	1.5×10^7	6.0×10^7	1.1×10^8
Th	8.5×10^0	8.5×10^4	3.4×10^5	6.0×10^5	8.5×10^5	3.4×10^6	6.0×10^6	8.5×10^6	3.4×10^7	6.0×10^7
Cs	3.4×10^0	3.4×10^4	1.4×10^5	2.4×10^5	3.4×10^5	1.4×10^6	2.4×10^6	3.4×10^6	1.4×10^7	2.4×10^7
Be	2.4×10^0	2.4×10^4	9.6×10^4	1.7×10^5	2.4×10^5	9.6×10^5	1.7×10^6	2.4×10^6	9.6×10^6	1.7×10^7
Sn	2.3×10^0	2.3×10^4	9.2×10^4	1.6×10^5	2.3×10^5	9.2×10^5	1.6×10^6	2.3×10^6	9.2×10^6	1.6×10^7
As	1.7×10^0	1.7×10^4	6.8×10^4	1.2×10^5	1.7×10^5	6.8×10^5	1.2×10^6	1.7×10^6	6.8×10^6	1.2×10^7
U	1.7×10^0	1.7×10^4	6.8×10^4	1.2×10^5	1.7×10^5	6.8×10^5	1.2×10^6	1.7×10^6	6.8×10^6	1.2×10^7
Ge	1.4×10^0	1.4×10^4	5.6×10^4	9.8×10^4	1.4×10^5	5.6×10^5	9.8×10^5	1.4×10^6	5.6×10^6	9.8×10^6
Ta	1.1×10^0	1.1×10^4	4.4×10^4	7.7×10^4	1.1×10^5	4.4×10^5	7.7×10^5	1.1×10^6	4.4×10^6	7.7×10^6
Mo	1.1×10^0	1.1×10^4	4.4×10^4	7.7×10^4	1.1×10^5	4.4×10^5	7.7×10^5	1.1×10^6	4.4×10^6	7.7×10^6
W	1.0×10^0	1.0×10^4	4.0×10^4	7.0×10^4	1.0×10^5	4.0×10^5	7.0×10^5	1.0×10^6	4.0×10^6	7.0×10^6
Tl	5.0×10^{-1}	5.0×10^3	2.0×10^4	3.5×10^4	5.0×10^4	2.0×10^5	3.5×10^5	5.0×10^5	2.0×10^6	3.5×10^6
Sb	3.0×10^{-1}	3.0×10^3	1.2×10^4	2.1×10^4	3.0×10^4	1.2×10^5	2.1×10^5	3.0×10^5	1.2×10^6	2.1×10^6
Se	1.2×10^{-1}	1.2×10^3	4.8×10^3	8.4×10^3	1.2×10^4	4.8×10^4	8.4×10^4	1.2×10^5	4.8×10^5	8.4×10^5
Cd	1.0×10^{-1}	1.0×10^3	4.0×10^3	7.0×10^3	1.0×10^4	4.0×10^4	7.0×10^4	1.0×10^5	4.0×10^5	7.0×10^5
Bi	8.5×10^{-2}	8.5×10^2	3.4×10^3	6.0×10^3	8.5×10^3	3.4×10^4	6.0×10^4	8.5×10^4	3.4×10^5	6.0×10^5
Ag	7.0×10^{-2}	7.0×10^2	2.8×10^3	4.9×10^3	7.0×10^3	2.8×10^4	4.9×10^4	7.0×10^4	2.8×10^5	4.9×10^5
In	5.0×10^{-2}	5.0×10^2	2.0×10^3	3.5×10^3	5.0×10^3	2.0×10^4	3.5×10^4	5.0×10^4	2.0×10^5	3.5×10^5
Hg	4.0×10^{-2}	4.0×10^2	1.6×10^3	2.8×10^3	4.0×10^3	1.6×10^4	2.8×10^4	4.0×10^4	1.6×10^5	2.8×10^5
PGE	1.3×10^{-2}	1.3×10^2	5.2×10^2	9.1×10^2	1.3×10^3	5.2×10^3	9.1×10^3	1.3×10^4	5.2×10^4	9.1×10^4
Te	5.0×10^{-3}	5.0×10^1	2.0×10^2	3.5×10^2	5.0×10^2	2.0×10^3	3.5×10^3	5.0×10^3	2.0×10^4	3.5×10^4
Au	2.5×10^{-3}	2.5×10^1	1.0×10^2	1.8×10^2	2.5×10^2	1.0×10^3	1.8×10^3	2.5×10^3	1.0×10^4	1.8×10^4
Re	4.0×10^{-4}	4.0×10^0	1.6×10^1	2.8×10^1	4.0×10^1	1.6×10^2	2.8×10^2	4.0×10^2	1.6×10^3	2.8×10^3

Clarke values are after Wedepohl (1995), metals arranged by decreasing clarkes

Deposits of several metals with limited demand like thorium also lack giant deposits because none have been delimited. Most of the remaining metals without “giants”: Ga, Ge, In, Sc and Tl have limited industrial demand and also have poor geochemical ability to locally accumulate. Their largest deposits, however of small to medium-size only, would attain the “world class” rank of Singer (1995) because of the way his definition is worded (10% of largest deposits, regardless of size). Although this book applies uniformly the geochemical accumulation magnitude divisions to maintain consistency, it is not fundamentalist and the largest deposits of giants-lacking metals are treated as well.

Clarke values used to determine magnitudes of metal concentration and accumulation: Although free of economic and technological bias, τ and CC figures are influenced by Clarke values. These, unfortunately, are not uniform and they change with the progress of science in time and, for the worse, with individual roughly contemporaneous authorities (compare the table of metal abundances and further discussion in Chapter 3). Clarke values for continental crust calculated by Wedepohl (1995), illustrated here by several trace metals, are 56 ppm Ni, 25 ppm Cu, 14.8 ppm Pb, 1.7 ppm U, and 2.5 ppb Au. Corresponding Clarke values from Rudnick and Fountain (1995) are 51 ppm Ni, 24 ppm Cu, 12.6 ppm Pb, and 1.42 ppm U. In contrast, Taylor and McLennan (1995) credit their “bulk continental crust” with 105 ppm Ni, 75 ppm Cu, 8 ppm Pb, 0.91 ppm U, and 3.0 ppb Au. The discrepancy in the crucial elements like Ni is about 200%, Cu 300%, Pb and U under 200%. The main reason for this discrepancy are the various proportions of the lower and upper continental crusts selected by the authors, and a controversy about the composition of the lower continental crust (is it mostly “basaltic”?). Taylor and McLennan (1995) gave more weight to the mafic component in the lower crust, hence their high Clarke values for the siderophile and chalcophile metals like Ni and Cu.

In this study are used the Clarke values of Wedepohl (1995); Fig. 2.2. It is obvious that if Clarke estimated by different authorities are used to calculate τ s and CCs, the definition and number of “geochemical giants” will change. With Taylor and McLennan (1995) Clarkes the number of nickel, copper and gold giants would decrease, the number of lead and uranium giants would increase.

Table 2.4. Proposed terminology of metal concentration in ore deposits based on Clarke of concentration (CC) (concentration factor)

CC lower threshold	Term	Examples of Cu deposits
1×10^5	extremely high	25%
1×10^4	very high	2.5%
1×10^3	high	0.25%
1×10^2	moderate	250 ppm
1×10^1	low	25 ppm
1×10^{-1}	sub-Clarke	2.5 ppm

NOTE: this is a terminology applicable uniformly to all metals, but uneven ability of metals to concentrate and resource economics result in different terms applied to specific metals in economic ores. The lowest cut-off grade of the “bulk mineable” Cu ores (e.g. porphyry coppers) is about 0.2% Cu now, so ores with average grade of 0.3–0.5% would be called low-grade, 2–5% Cu high grade, 10% plus extremely high grade.

2.3. Dimension, complexity and hierarchy of metallic deposits, districts

Metallic “deposits” (a generic term), the names of which are recorded in databases and named in the literature, are highly nonuniform in terms of dimension and internal complexity. Seven examples of actual deposits below illustrate this point (Figs. 2.3 a–d):

1. The giant Mountain Pass rare earth deposit in California (Section 12.9) is an ideal “simple giant”: it is a single, internally homogeneous lonely orebody that measures about 760×70 m and has a sharp boundary against its wallrocks.
2. Kidd Creek, the massive sulfide Zn, Cu, Ag giant in Ontario (Chapter 10), is also easy to deal with but the deposit is internally complex (it consists of a massive sulfide lens floored by stringer stockwork) and the continuity is interrupted by deformation.
3. Broken Hill supergiant Pb, Zn, Ag zone in Australia (Chapter 14) is a 7 km long virtually continuous mass of eight coalescing separate high-grade lodes of comparable character, but with varying metal ratios (“Lead” and “Zinc” lodes plus several lower-grade bodies). The uniformity is further complicated by the presence of oxidation zone (gossan), and sulfides remobilized along shears.
4. Collahuasi, in the Chilean Andes (Chapter 7) is a composite ore field (called district in Masterman et al., 2004) that measures about 15 × 10 km across and consists of several deposits

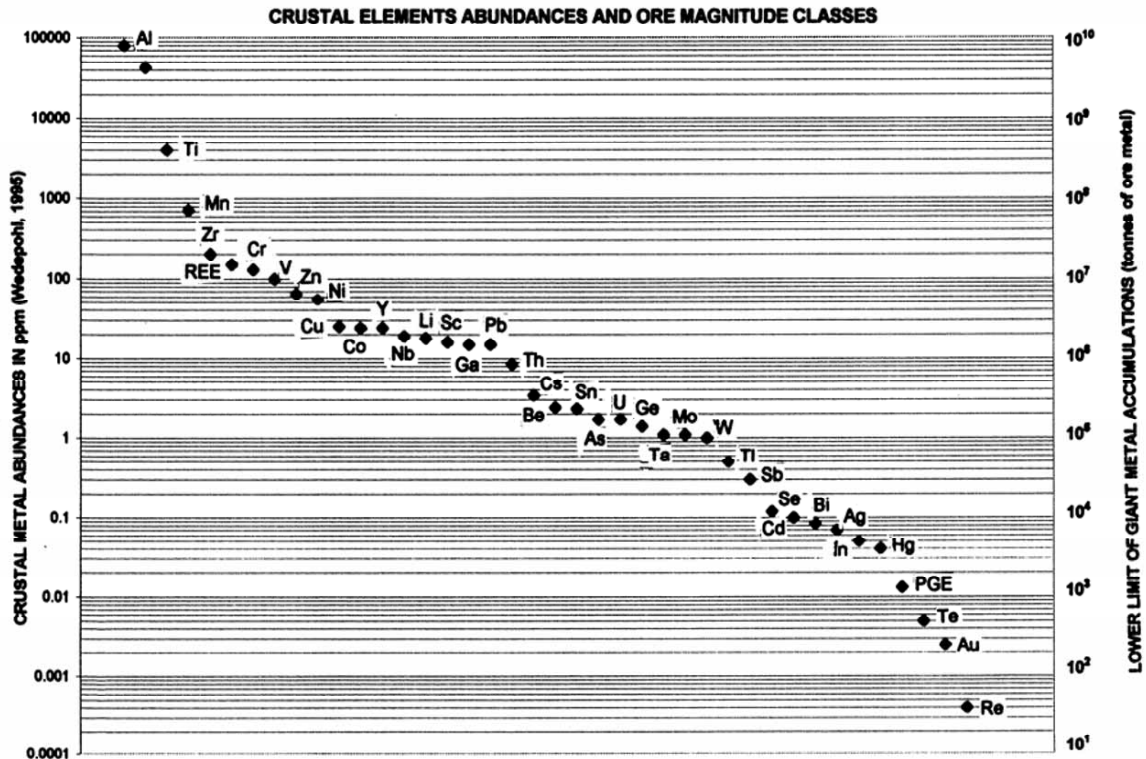


Figure 2.2 Graph showing lower limits (thresholds) of giant deposits (right scale) as related to crustal abundances (clarkes) of metals

of different types: disseminated porphyry Cu with hypogene, secondary sulfide, and oxide copper intervals; Cu, Au, Ag veins; and exotic infiltration Cu deposits in gravels.

5. Faro-Anvil Pb, Zn, Ag district in Yukon (Chapter 13) is an elongated NW-SE trending zone about 50 × 10 km across that contains seven delineated massive sulfide orebodies and scattered ore occurrences.
6. Witwatersrand (Chapter 11) is a remnant of a late Archean predominantly sedimentary basin measuring about 500 × 300 km that contains nine areas of concentrated mineralization ("goldfields") and several scattered lonely ore occurrences. Most of the surficial outcrop in the Witwatersrand is, however, occupied by younger geological units largely devoid of mineralization, and the gold is virtually confined to the Central Rand Group that has the best continuity in the (often deep) subsurface. Each named Goldfield measures between 20 and 100 km along its longer axis (so it corresponds to a "district") and it consists of several extensive sheet-like orebodies of auriferous conglomerates, there called "reefs".

7. The central Andean copper and gold belt (Chapters 6, 7) is a 2,500 km long, 500 km wide linear north-south zone of densely scattered predominantly Meso-Cenozoic Cu, Mo, Au, Ag deposits of several types (but predominantly porphyry Cu-Mo) formed within a long lasting consuming continental margin. It is bordered by gaps in, or absence of, strong mineralization.

The above examples demonstrate the considerable range of dimensions (only the length and width dimensions are considered above, to which should be added the depth dimension), complexity and hierarchy of sites of metal accumulation, yet all the above categories tend to be jointly manipulated in order to reach various metallogenic conclusions. Accepting at par and comparing the Mountain Pass-like single orebodies with Witwatersrand-type basins exceeds the proverbial comparison of apples and oranges: it is more like comparing a single wheel with a locomotive. In this book and the GIANTDEP database the rank of entries (localities, "deposits") is always indicated.

Hierarchical listing is frequently used (in GIANTDEP, the Witwatersrand entries occupy three ranks: Witwatersrand basin→ Klerksdorp Goldfield → Vaal Reef).

There is more discrepancies in many reviews of metallic deposits and in databases sourced from the heterogeneous, especially international, literature. The wide reach of the term “ore deposit” has been mentioned above and the same applies to “district”. The term “district” is, moreover, used as (i) a purely political administrative unit (e.g. Keonjhar district, India); (ii) as a territory administered by a mine registrar (e.g. Robinson district in Nevada that includes the Ely ore field); (iii) as a territory of densely distributed and/or mutually related ore occurrences (e.g. the Faro-Anvil district, the preferred usage here). There are more terms in the literature that require scrutiny. Mine is a producing facility and/or a property and it may (i) coincide with a single orebody or an ore deposit; (ii) include several ore deposits (e.g. the Kosaka or Hanaoka mines in the Hokuroku district of Honshu) or (iii) include a portion of a continuous ore deposit within a mine lease (e.g. the Hemlo gold ore deposit is subdivided into three properties, the Broken Hill NSW lode had up to seven major properties in various times). The Russian term “ore knot” (rudnyi uzel) corresponds to ore field or ore district and the same applies to the western term “goldfield”. Zone (ore zone), trend (e.g. Carlin Trend), belt (e.g. Whitehorse copper belt) are usually used for elongate (linear) ore-bearing territories in the ore field, district, regional (e.g. the African Copperbelt) to continental (e.g. the Andean Copper Belt) ranks.

There are more ore site terms that have a genetic connotation, or are used in the context of a specific theory, branch of science or a model. The term “province” (e.g. metallogenic province in general like Abitibi in Canada; Bolivian tin province) refers to a region with a distinct mineralization, especially one dominated by a single metal. Metalloctect, popular in the European literature of the 1970s–1980s, has a distinct tectonic connotation that implies prominent fault control. This does not work well with deposits formed in sedimentary basins or at the paleosurface where other controls are predominant. In this book the term metallogene is used for a set of processes, conditions and environments working together to produce a distinct metallogenic pattern, and the affected territory itself (e.g. the Bushveld metallogene incorporates the processes of derivation, differentiation, fractionation, emplacement and cooling of mafic-ultramafic magmas responsible for the distinct Cr, Fe, Ni, Ti, V, and PGE metallogeny).

Traditional names of localities common in the literature like Victoria Goldfields, Carlin Trend, African Copperbelt, and others are retained in this work but they are provided with a rank qualifier in the GIANTDEP database and in tables and diagrams. Only localities of corresponding rank are mutually contrasted, compared and employed to reach quantitative conclusions. Ranks of sites of industrial metal(s) accumulations (“localities”, “deposits”) used in this book, from small and simple to large and complex, are summarized in Table 2.5 and Fig. 2.4.

Configuration of giant localities in database entries:

Simple internally homogeneous deposits like Mountain Pass enter database as they are, their magnitude expressed by ore tonnage, grade, and/or metal content. Composite deposits like porphyry coppers with reserves residing in both hypogene and secondary-enriched or oxidized portions, are entered as a whole or as two, or three, separate entries. This is most useful when all components are of giant magnitude. Giant size localities (ore field, district, belt, etc.) that are composites of two or more orebodies/ore deposits, allow a variety of possible configurations. Some contain one or more giant members of lower rank (deposits or orebodies), plus deposits of lesser than giant size. Others contain only deposits of sub-giant size that reach the required “giant” threshold only after addition. In the absence of clear and natural delimiters such as prominent gaps in ore density, geological change or different age/style of deposits, “giant manufacturing” is a highly subjective process. and it account for the many discrepancies in published statistics related to ore deposits of exceptional size

Expressions used in text and tables: The ore magnitude terms based on clarke values are used consistently in this book and the magnitude terms are shown in quotation marks (“giant”, “giant deposit”, “large orebody”, “super-giant district”). The term “near-giant” is used for deposits not yet of the giant rank, but close to it and likely to become a “giant” in the near future while the exploration continues. In few instances the term “geochemical giant” is used for metal accumulations of the geochemically “giant” magnitude, but with lesser to none industrial (economic) importance under the present conditions.

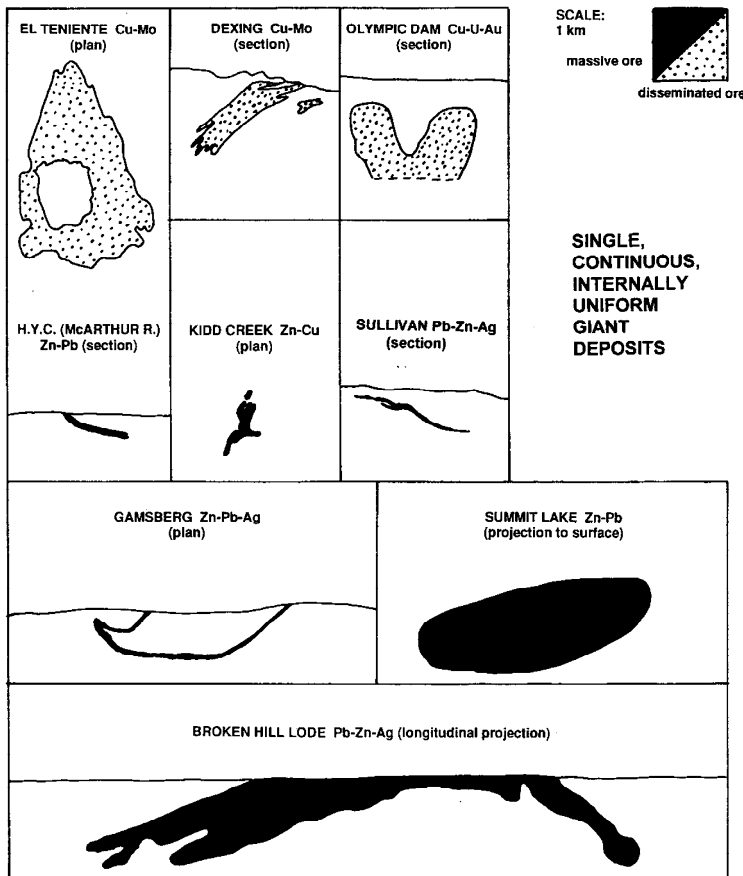


Figure 2.3a. Configuration, complexity and “footprint” of selected examples of “giant” deposits: single, continuous, internally uniform orebodies

2.4. The share of “giant” metal accumulations in global metal supplies

Based on the quantitative criteria outlined above, there were 486 entries (records) that qualify as “giant”, and 61 entries that qualify as “supergiant”, in the 1999 version of the GIANTDEP database, on which were based the conclusion in Laznicka (1999). New additions (up to mid-2009) are included in the Appendix database, but have not been used for new calculations. The database entries (one entry per metal/locality, hence when one locality contains giant accumulations of three metals, it is listed three times) translate into 446 “localities” in the 1999 version. The localities that range in dimension and complexity from simple, single ore deposits to large composite metalliferous “basins” are sometimes arranged hierarchically; that is, the greater, first or second order divisions include smaller, third order units that correspond to the bulk of independent (non-hierarchical) primary entries in

the database). There were 547 primary entries, 51 second order divisions and one first order division (the Witwatersrand “Basin”). Although the bulk of entries are the “classical” (highly geochemically enriched) deposits or districts, there were 57 entries that are low-grade or otherwise unsuitable for immediate production, but they represent a significant local accumulation of metals to be perhaps exploited in the future. This does not include the metalliferous materials on ocean floor or sea water (Chapter 4).

Table 2.6. shows the global endowment (that is cumulative past production and remaining or new reserves and resources) of all industrial metals. The endowment used here corresponds to the “maximum endowment” shown in column 4, Table 4 in Laznicka (1999), as the available data are still insufficient to produce an absolutely accurate figures (compare the values assembled by the U.S. Geological Survey shown here in Table 1.5).

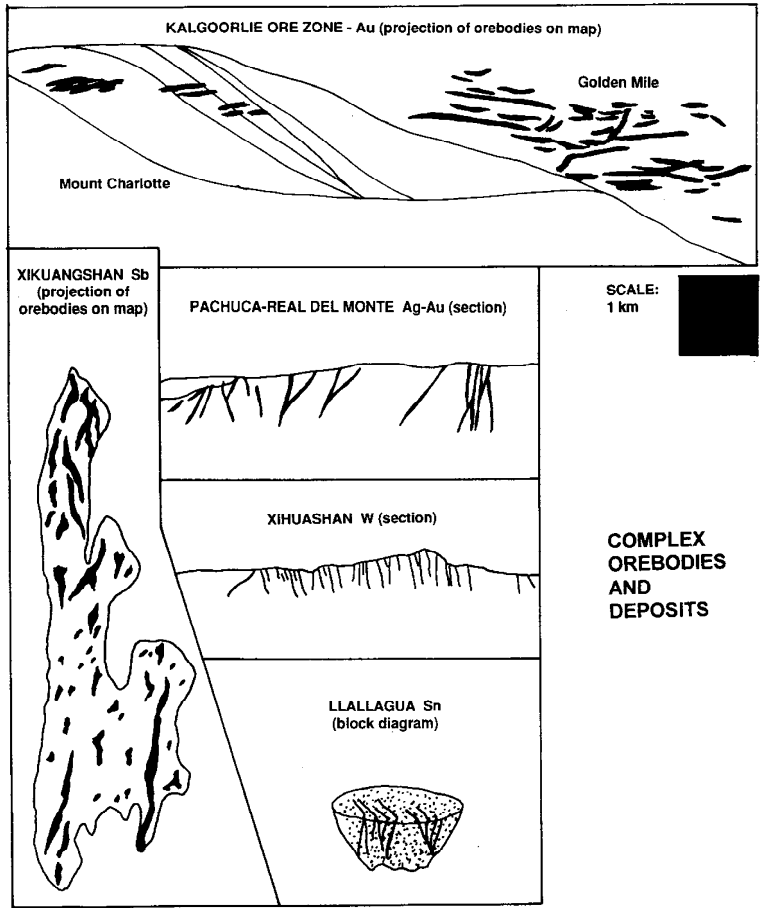


Figure 2.3b. Configuration, “footprint” and internal complexity of “giants”: complex orebodies and deposits

Table 2.7a. indicates the very uneven numbers of giant deposits of the various metals, and the impressive share of the giant and super-giant deposits in storing the world’s resources of industrial metals (the figures include both the past production and the metals that remain, hence they are not indicative of what is still left in ground). The dominant role of the “giants” as the warehouse of metals in present time follows quite convincingly from the numbers, despite the limited accuracy.

As expected, the absolute magnitude of metal accumulations generally increases with the increasing geochemical abundance of elements (the McKelvey’s Law, McKelvey, 1960; Erickson, 1973), but the increase is not systematic. This is due to several causes some of which are entirely extraneous to geology, while the others are probably the consequence of the geochemical behaviour of elements in the various rock- and ore-forming systems. One obviously extraneous factor influencing the frequency of “giants” of several

metals is the differences in price and market demand, which do not closely correlate with crustal abundances of elements. The high-demand metals like Fe, Cu, Zn, Au have been eagerly sought and exploited for centuries, hence every newly found deposit usually goes into production within few years and the inventory of localities grows. The limited-demand metals such as Zr, Nb, REE are mined and supplied by several specialty producers serving captive markets. The already known but substantially unexploited resources of the latter metals are sufficient for several hundred years at the present rate of consumption, so there is little incentive for vigorous exploration, hence the inventory of known deposits increases slowly if at al. The inventory of deposits of the almost nil-demand metals like thorium is stagnant and fragmentary. The largest recorded Th resources are in complex deposits where other metal is the principal economic commodity and the Th quantities, that are not being recovered at present,

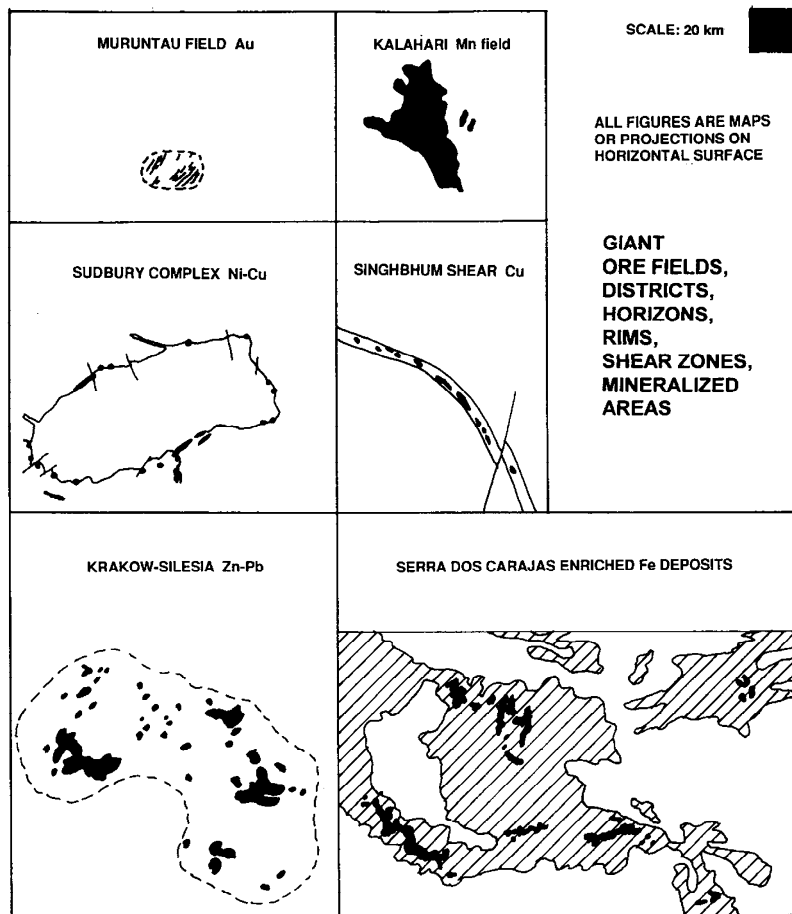


Figure 2.3c. Configuration, “footprint” and internal complexity of “giants”: ore fields, districts, horizons, shears

have been calculated from published analyses. Examples include the U-conglomerates at Elliot Lake, Ontario; the Nb-carbonatite at Araxá; and others.

Certain “cheap” metals are grossly undervalued in relation to their geochemical scarcity. The most striking example is antimony: Sb that has clark of only 0.3 ppm sells for about USD 4.0/k in contrast with the more abundant Ni, with clark of 55 ppm, that normally sells for about USD 7/k. The main reason for the poor performance of antimony is the loss of its principal past use in typography, hence a collapse of demand. Another reason for the antimony bargain price is that it forms highly concentrated deposits that are cheap to mine and process; the largest deposits are in countries with low cost labor and logistics (China, South Africa, Bolivia). Antimony and mercury deposits in fact, especially the three super-giants Almadén-Hg, Spain; Idrija-Hg, Slovenia; Xikuangshan-Sb, Hunan, China, have achieved the greatest

magnitudes of the relative metal concentration and accumulation ever recorded! (compare the plot of Almadén [Hg] and Xikuangshan [Sb] on Fig. 2.6, high in the 10^4 and 10^5 range of concentration factors and in the 10^{12} area of accumulation magnitudes).

Column four in Table 2.6 gives the number of giant and super-giant deposits of each metal included in the GIANTDEP database. Copper is the undisputed winner followed by gold. The number-of-giants sequence, arranged by decreasing number of entries, is as follows (numbers of entries, out of 523, from Table 2.6 are in brackets): Cu (103); Au (99); Pb (55); Ag (43); Mo (41); Sb (24); Sn (22); Zn (21); Hg (19); W (12); Fe (11); As (9); U (9) Mn (9); Ni (8); PGE (7); Nb (6); REE (5); Bi (5); Co (3); Cr (3); Zr (3); V (2); Cd (1); Th (1); Ti (1); Y (1). The following metals have not reached the “giant” threshold: Al, Be, Ga, Ge, In, Sc, Se, Ta, Te, and Tl, for a variety of reasons. Aluminum is too geochemically abundant (it is the most abundant

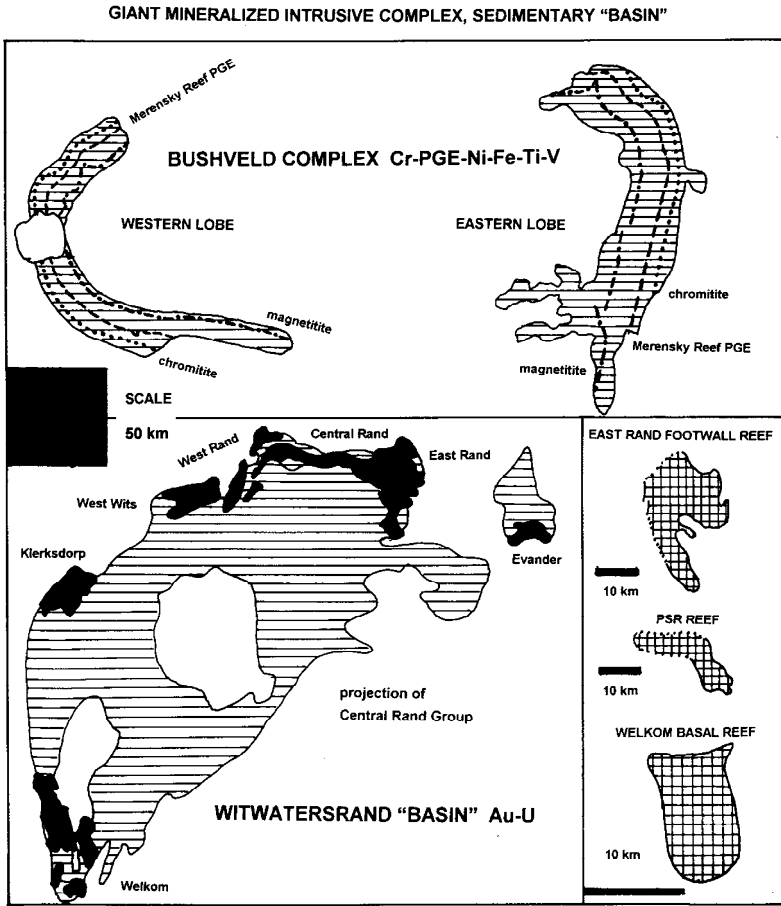


Figure 2.3d. Configuration, internal complexity of “giants”: large magmatic complexes and sedimentary basins

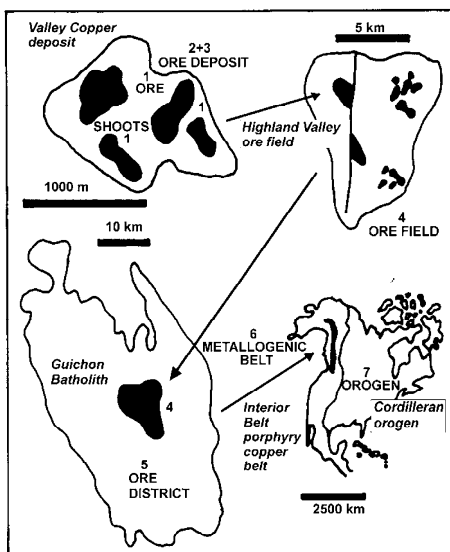


Figure 2.4. Ranks and hierarchy of mineralized objects exemplified by the Highland Valley porphyry Cu ore field, British Columbia, Canada (read Chapter 7 for description)

Table 2.5. Ranks and hierarchy of metals accumulations

Rank	Common names	Dimensions	Characteristics
1	Ore shoot, component of composite orebody	X–X00 m	Entity within or immediately adjacent to an orebody (rank 2) with some special characteristics (e.g. high grade, different metals) or a different style in composite orebodies (e.g. footwall stockwork in VMS, oxidation zone, band of sheared ore)
2	Orebody, ore bed, ore layer	X0–X,000 m	Single body of ore material like massive sulfide lens, ore vein, sedimentary ore bed, mass of altered rock with disseminated sulfides, residual ore blanket
3	Ore deposit (deposit, e.g. Cu deposit). Also used as general term in lists of various ranks	X00–X,000 m	Equivalent to orebody in single body ore deposits or a set of close orebodies of the same (e.g. vein swarm) or different (e.g. veins, replacements, breccia bodies, enrichment blankets) styles and ore metals
4	Ore field; ore center; ore knot; ore complex	~5 to ~20 km	Group of two or more orebodies/ore deposits of the same or different types, but usually genetically related
5	Ore district (district); large ore complex, trend, zone	~10 to 100 km	Territory containing one or more repetitive and usually genetically related styles of orebodies; strong administrative influence
6	Mineralized region, belt, basin, geological division, province	~50 to 500 km	Territory or geological division, structure with numerous deposits of one or few metals of repetitive style. Witwatersrand “basin”, Victorian Goldfields province, Iberian Pyrite Belt, African Copperbelt
7	Continental scale ore belts, provinces, basins	~300 to 5,000 km	Distinctly and/or densely mineralised continuous territories that can be shown on page-size world maps. Andean Cu-Au belt and its segments (e.g. Central Chile Cu-Au Belt); SE Asian Tin Belt; Basin-and-Range ore province (in USA and Mexico)

NOTES: 1 = smallest rank. X stands for several, e.g. X km = several kilometers. Extensive, formerly continuous ore horizons, beds, layers and units such as the chromitite bands, Merensky Reef and Magnetite layers of the Bushveld complex combine characteristics of an orebody (Rank 2) with dimensions of a mineralized region (Rank 6). The same applies to the Cretaceous West Siberian ironstone horizon, Eastern Australian (Pacific) heavy minerals sands province, Guinea bauxite province, Pacific floor Fe–Mn nodules province.

metal in the crust with clarke of 8%, not counting Si), hence the threshold for the giant magnitude of Al deposits is 8 billion tons of contained Al. No deposit or even an extensive area of bauxite, presently the only viable Al ore, approaches such an endowment. Once anorthosite becomes an industrial aluminum ore, many anorthosite massifs of today will achieve the “giant” status. Ta, as geochemically abundant as Mo (1.1 ppm); and Ga and Sc, as geochemically abundant as Pb (15 ppm), tend to remain dispersed and substitute for other elements in minerals’ lattices. Ta forms low concentrated accumulations in the highest fractionated granitic and alkaline systems, but Ge and Sc rarely form minerals of their own. Gallite is a mineralogical rarity known from two localities only and so is thortveitite; besides, market for Ga and Sc is extremely limited. Se, Tl, Te and In are rare to moderately rare metals that accumulate in sulfide deposits and are recovered from electrolytic residue,

to supply the very small market (Staff, U.S. Bureau of Mines, 1985).

The largest accumulations of each metal

Table 2.7a, b. lists and Fig. 2.5. show graphically the single largest deposits or districts for each industrial metal. When more than one locality example for a single metal are listed, usually the first entry has the highest magnitude of metal accumulation but a very low-grade which renders it currently uneconomic (e.g. the Chattanooga Shale, Tennessee-U; Chapters 1 and 13). The second entry (and the rest of single entries) is (are) the presently economically viable “classical” metal deposits (e.g. Olympic Dam, South Australia-U). Fig. 2.6. is a plot of these deposits on a graph that contrasts metal concentrations (as clarke of concentration; vertical axis) and metal accumulations (as tonnage accumulation index; horizontal axis). As already

Table 2.6. Global Endowment of Ore Metals and Share of the giant and supergiant deposits from Laznicka (1999), reprinted courtesy of Economic Geology

Metal	Total world production, t	Global endowment maximum, t	Number of giants	Metal content in all giants
Al	505 mt	1.2 bt	0	0
Fe	34 bt	3,000 bt	11	2,510 bt
Ti	153 mt	12 bt	1	9.50 bt
Mn	835 mt	7.7 bt	9	7.44 bt
Zr	18.6 mt	470 mt	3	435 mt
REE	1.04 mt	280 mt	5	98 mt
Cr	430 mt	9.2 bt	3	4.18 bt
V	861 kt	2.10 mt	2	2.06 bt
Zn	225 mt	620 mt	21	315 mt
Ni	28.3 mt	145 mt	8	121 mt
Cu	354 mt	1.35 bt	103	1.23 bt
Co	1.15 mt	15 mt	3	12 mt
Y	14 kt	5 mt	1	3.0 mt
Nb	272 kt	110 mt	6	104 mt
Ga	1,103 t	110 kt	0	0
Pb	170 mt	338 mt	55	302 mt
Th	13 kt	1.62 mt	1	1.16 mt
Hf	X00 t	X0 kt	0	0
Be	12.8 kt	81.6 kt	0	0
Sn	12.5 mt	26 mt	22	23.8 mt
As	3.32 mt	21 mt	9	8.65 mt
U	1.86 mt	32 mt	9	3.45 mt
Ge	1,100 t	110 kt	0	0
Ta	4,700 t	400 kt	0	0
Mo	2.43 mt	28.4 mt	41	27.4 mt
W	500 kt	4.7 mt	12	3.63 mt
Tl	310 t	17 kt	0	0
Sb	2.49 mt	7.5 mt	24	6.97 mt
Se	56.6 kt	750 kt	1	225 kt
Cd	744 kt	2.2 mt	1	1.08 mt
Bi	167 kt	600 kt	5	520 kt
Ag	947 kt	1.37 mt	43	859 kt
In	2,800 t	12 kt	0	0
Hg	413 kt	980 kt	19	950 kt
PGE	7,160 t	103 kt	7	90.8 kt
Te	4,900 t	42 kt	1	1,000 t
Au	99.5 kt	177 kt	99	97.2 kt
Re	X00 t	X0,000 t	0	X,000 t

NOTES: Metals are arranged by decreasing clarke values. Total recorded global production to 1992, compiled by S.M. Laznicka from Minerals Yearbook. Gaps filled by extrapolation

Maximum global endowment = compiled sums of global past production of ore metals plus remaining or new reserves and some resources of delineated deposits, with several calculated metal contents of geological bodies like the Bushveld metalliferous layers, and calculated contents of some unrecovered trace and associated metals in ores mined for other elements. Because of incompleteness of the global endowment data the values shown are considered as maxima. To reduce confusion, metal tonnages are shown in tons (t), thousand tons (kt), million tons (mt) and billion tons (bt)

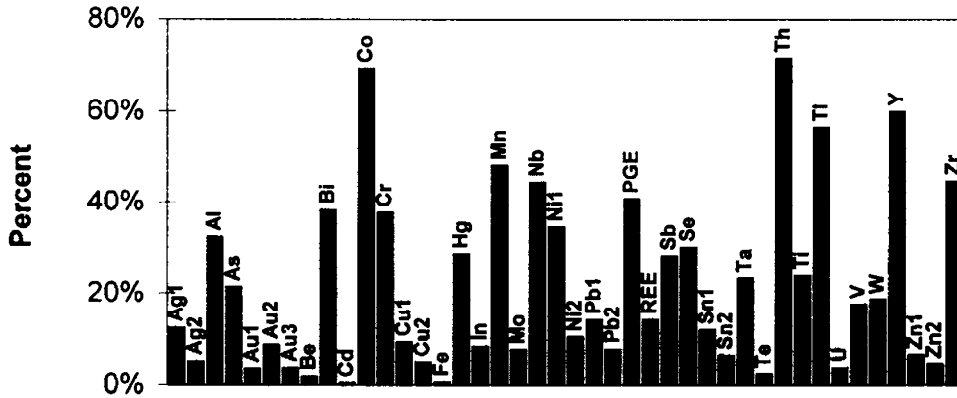


Figure 2.5. Share of giant deposits of the global ore metals endowment (compare Table 2.6). From Laznicka (1999), reprinted courtesy of Economic Geology

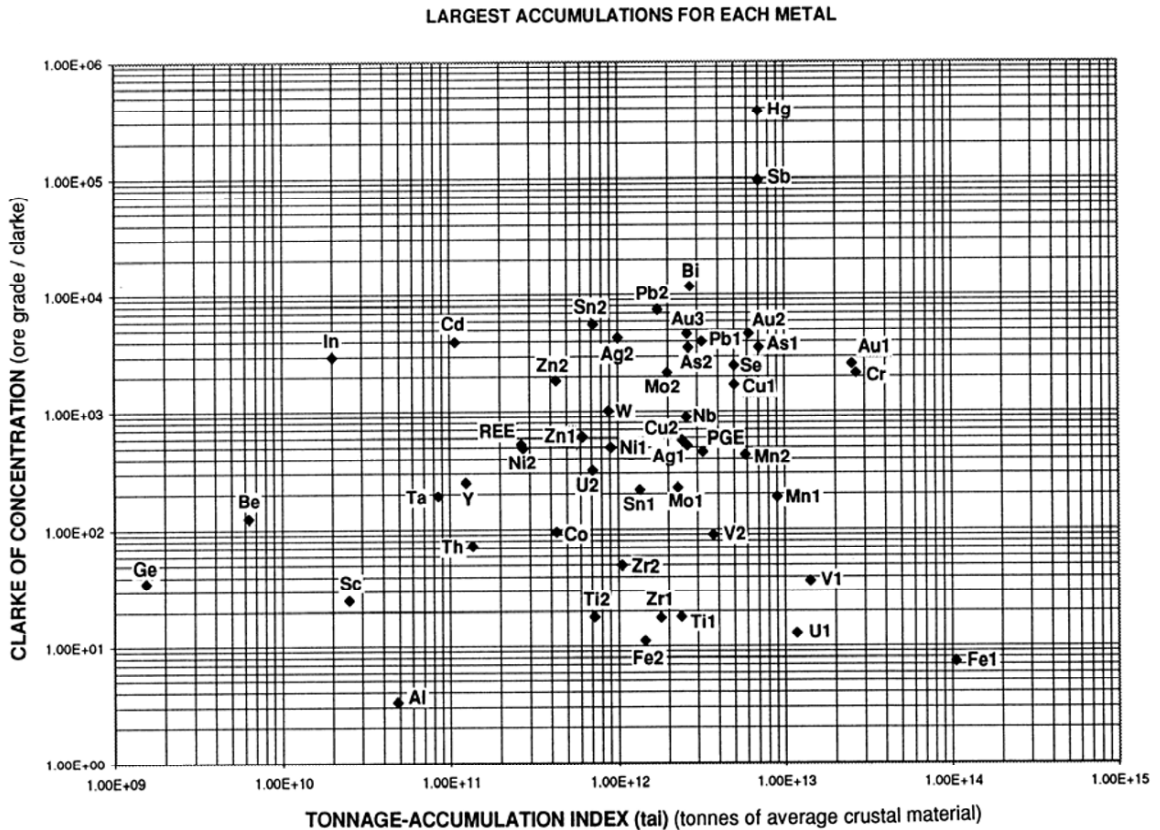


Figure 2.6. Plot of the largest deposits/districts of industrial metals into a clarke of concentration versus tonnage accumulation index graph

mentioned, two Hg and Sb deposits stand out from the rest in terms of the magnitude of metal accumulation, at substantial metal grades. The rest of metal entries plots as what looks like a random cluster with some general trends faintly suggested.

The metals that prefer dispersal to local concentration are on the left, the high-clarke metals (Al, Fe) near the bottom, the high-grade ore forming metals (most of which are hydrothermal) are in the upper half. It should be

realized that the plot represents single most exceptional localities out of exceptional populations, hence most of these deposits are in some way unique and not necessarily representative of the remaining “giants” and lesser

size deposits of corresponding metals. The geological reasons for metals super-accumulation, as much as they can be determined or at least guessed, are discussed in Chapter 15.

Table 2.7a. Single largest deposits/districts of the industrial metals and their share of global endowment (based on GIANTDEP 2, 1999, to preserve original conclusions; please read Table 2.7b below for updates)

Metal	Largest deposit/district	Object	Metal content, t	Grade	% of max. endowment
Al	Boké-Gaoual, Guinea	area	3.88 bt	26.5 %	32.33
Fe	Alegria, Brazil*	deposit	62 bt	48.0 %	0.62
Ti	Bushveld Main Magnetite Seam, South Africa	unit	2.88 bt	7.2 %	24.00
Mn	Kalahari-Mamatwan, South Africa	deposit	4.19 bt	31.3 %	48.16
Zr	Lovozero eudialyte lujavrite unit, Russia	unit	210 mt	1.0 %	44.68
REE	Tomtor, Anabar Shield, Russia	deposit	40 mt	8.0 %	14.29
Cr	Bushveld chromitite seams, South Africa	unit	3.47 bt	28.0 %	37.72
V	Bushveld Main Magnetite Seam, South Africa	unit	371 mt	0.9 %	17.67
Zn-1	Kraków-Silesia Muschelkalk Basin, Poland	basin	40 mt	4.0 %	6.45
Zn-2	Broken Hill, N.S.W., Australia	ore zone	28 mt	12.0 %	4.52
Ni-1	New Caledonia laterite-saprolite blanket	area	50 mt	2.75 %	34.48
Ni-2	Talnakh-Oktyabrskoye, Russia	ore field	15 mt	2.7 %	10.34
Cu-1	Copperbelt, Katanga portion, DRC Congo	ore belt	125 mt	4.25 %	9.26
Cu-2	El Teniente, Chile	deposit	66 mt	1.31 %	4.89
Co	Copperbelt, Katanga portion, DRC Congo	belt	10.4 mt	0.23 %	69.33
Y	Tomtor, Anabar Shield, Russia	deposit	3 mt	0.6 %	60.00
Nb	Seis Lagos, Brazil	deposit	48.9 mt	1.7 %	44.45
Ga	Brockman, Western Australia, Australia	deposit	640 t	150 ppm	0.6
Pb-1	Viburnum Trend, S.E. Missouri, U.S.A.	ore zone	48 mt	4.0 %	14.20
Pb-2	Broken Hill, N.S.W., Australia	ore zone	26 mt	11.3 %	7.69
Th	Araxá, Brazil	deposit	1.16 mt	0.62 %	71.60
Be	Strange Lake, Labrador, Canada	deposit	15.1 kt	300 ppm	1.85
Sn-1	Kinta Valley placers, Ipoh, Malaysia	area	3.10 mt	0.05 %	11.92
Sn-2	Dachang, Jiangxi, China	ore field	1.65 mt	1.3 %	6.35
As	Rio Tinto, Spain	ore field	4.50 mt	0.6 %	21.43
U	Olympic Dam, South Australia	deposit	1.20 mt	540 ppm	37.5
Ge	Tsumeb, Namibia	deposit	2,160 t	5 ppm	2.0
Ta	Ghurayyah, Saudi Arabia	deposit	93.3 kt	212 ppm	23.33
Mo	Climax, Colorado, U.S.A.	deposit	2.18 mt	0.24 %	7.68
W	Verkhnye Qairakty, Kazakhstan	deposit	880 kt	0.102 %	18.72
Tl	Meggen, Germany	deposit	960 t	24 ppm	56.47
Sb	Xikuangshan, Hunan, China	ore field	2.11 mt	2.9 %	28.13
Se	Rio Tinto, Spain	ore field	225 kt	30 ppm	30.00
Cd	Tsumeb, Namibia	deposit	10.8 kt	40 ppm	0.49
Bi	Shizhouyuan, Hunan, China	deposit	230 kt	100 ppm	38.33
Ag-1	Lubin Kupferschiefer district, Poland	district	170 kt	4 ppm	12.44
Ag-2	Potosi (Cerro Rico), Bolivia	deposit	70 kt	30 ppm	5.12
In	Mount Pleasant, New Brunswick, Canada	ore field	100 t	15 ppm	8.33
Hg	Almadén, Spain	deposit	280 kt	0.15 %	28.57
PGE	Merensky Reef, Bushveld, South Africa	unit	42 kt	6.0 ppm	40.78
Te	Cripple Creek, Colorado, U.S.A.	ore field	1000 t	8.5 ppm	2.38
Au-1	Central Rand Group, Witwatersrand, S. Africa	basin	63 kt	6.5 ppm	35.60
Au-2	Welkom Goldfield, Witwatersrand, South Africa	ore field	15.3 kt	11.6 ppm	8.64

* There is probably an order of magnitude error in the original source; the Fe content is more likely 6.2 bt. or less. This table is from Laznicka (1999) and has not been updated in order to match related applications

Table 2.7b. Single largest deposits/districts of the industrial metals: 2009 update based on GIANTDEP 4 in Appendix (only entries that have changed since 1999 are included)

Metal	Largest deposit/district	Object	Metal content, t	Grade
Fe1	Kursk Magnetic Anomaly	region	35 bt	50.0+ %
Fe2	Hamersley Basin, Australia	basin	19.5 bt	60+ %
REE	Bayan Obo, China	deposit	45 mt	4.0 %
Zn-1	Kraków-Silesia Basin, Poland	basin	28 mt	3.8 %
Zn-2	Red Dog, Alaska	ore field	31 mt	16.6 %
Ni-2	Noril'sk-Talnakh, Russia	district	23.2 mt	1.77 %
Cu-2	El Teniente, Chile	deposit	98 mt	0.63 %
Pb-1	Viburnum Trend, S.E. Missouri, U.S.A.	ore zone	40 mt	4.0 %
Pb-2	Broken Hill, N.S.W., Australia	ore zone	28 mt	10.0 %
Be	Shizhuyuan, China	deposit	100.0 kt	0.12 %
Sn-2	Gejiu, China	ore field	2.45 mt	1.1 %
U	Olympic Dam, South Australia	deposit	1.98 mt	216 ppm
Ge	Red Dog, Alaska	deposit	18.7 kt	100 ppm
Mo	Climax, Colorado, U.S.A.	deposit	2.70 mt	0.24 %
Cd	Uchaly, Russia	deposit	33.75 kt	150 ppm
Bi	Shizhouyuan, Hunan, China	deposit	100 kt	590 ppm
Ag-2	Potosi (Cerro Rico), Bolivia	deposit	115 kt	102 ppm
In	Uchaly, Russia	ore field	3150 t	15 ppm
PGE	Merensky Reef, Bushveld, South Africa	unit	30.8 kt	6.0 ppm
Re	Dzhezkazgan, Kazakhstan	ore field	2800 t	1.4 ppm
Te	Red Dog, Alaska	ore field	15,888 t	85 ppm

NOTE: Many minor elements (Cd,Se,Te,In,Re) are not (fully) recovered from complex ores and the deposits shown need not be the largest accumulations of these metals; they are included here because their trace metals contents have been published (or orally communicated)



Laochang ore field in the Gejiu Sn-Pb-Zn-Ag district, Yunnan, SW China: the world's largest tin district (~2.5 mt Sn).



Broken Hill, New South Wales, Australia, the world's largest lead ore field. The old Junction Mine, inactive but still standing (*top*) and the former Zinc Corporation Mine (*bottom*); PL 1981, 2007