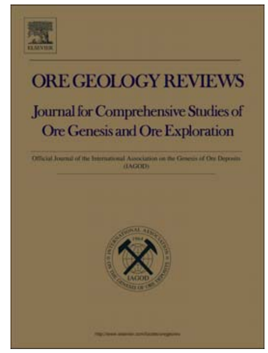
Accepted Manuscript



Giant Metallic Deposits-a Century of Progress

Peter Laznicka

PII: S0169-1368(14)00055-9
DOI: doi: 10.1016/j.oregeorev.2014.03.002
Reference: OREGEO 1186

To appear in: *Ore Geology Reviews*

Received date: 23 October 2013
Revised date: 6 March 2014
Accepted date: 9 March 2014

Please cite this article as: Laznicka, Peter, Giant Metallic Deposits-a Century of Progress, *Ore Geology Reviews* (2014), doi: 10.1016/j.oregeorev.2014.03.002

Giant Metallic Deposits-a Century of Progress

Peter Laznicka

Metallogenica Consulting and Adelaide University

e-mail: plaznicka@dodo.com.au

address: 64 Lochside Drive, West Lakes, SA 5021, Australia

Abstract

Giant (and super-giant) metallic deposits are defined as those that store the trace metal (and some major metal like Fe, Al) equivalent in 10^{11} (10^{12}) tons of continental crust in Clarke (mean crust content) concentration. Deposits of metallic ores that have very contrasting Clarke values (like Fe, Cu and Au) can be compared on geochemical basis, with political-economic and technologic factors minimized. Under these terms, there are now 1171 giant and 137 supergiant accumulations of 37 metals worldwide, contained in 915 deposits, as several deposits have two or more giant metal accumulations (Olympic Dam has 5). These deposits store and supply between 60 and 95% of global metallic resources on land, with several individual deposits monopolizing the supply. It is predicted these exceptional deposits will remain the principal metal source for the industry at least through this century. The "ore giants" are dominated by gold and copper (278 and 268 entries), followed by Mo (166), Ag (119) and Pb (90).This metal selection is more the consequence of demand and price than geological availability, proving that when there was a demand and the "right" price, the resources industry has been able to discover and develop new deposits to satisfy this demand. This may change in the future so unconventional metal sources are reviewed and compared with the classical, high concentration factor ores.

I have not been able to find a single case where a giant deposit would be a unique, one-of-a-kind product. In all instances, the ore giants are magnitude end members of a population of lesser deposits of the same, or similar, type so they are only quantitatively distinct from the rest. For that reason discovery of the ore giants is statistical and cannot be exclusively targeted, despite the fact that in some cases the "giants" were among the first deposits discovered. Although the ore giants are not qualitatively different from the lesser members of the same type, they are the product of the best optimized mineral system. A number of metal accumulation magnifiers have been suggested in the literature and they are briefly reviewed here.

More than 70% of the ore giants have been discovered in the past sixty years; the discovery rate grew steadily since the Industrial Revolution in the 19th Century when a number of new chemical elements had been discovered, to accelerate in the 1890s, then again in the 1950s.

The 1965-1970 and 1990-1995 intervals had the greatest number of giant deposits discovered (38 and 43, respectively) and this not only replenished the consumed metals, but provided a significant surplus. These periods may have been discovery peaks followed by diminishing ore finding rate, suggesting future metal supply scarcity. With continuing depletion of ore discoveries exposed at the surface the number of deposits found under cover has grown almost exponentially; by 2010, close to 150 partially to completely buried ore giants have been found, some in a depth approaching 3000 m. This has only been possible by continuously increasing complexity and cost of ore finding, from visual on-foot discoveries prevalent before 1950 to the instrument-assisted discoveries by corporate teams. The prevalent technique of ore discovery (followed by proving) is drilling, positioned by geochemical and geophysical anomalies, in turn the product of practical geological models and creative human reasoning. As metal mining is an economic activity made possible by geological availability of resources, it is believed that the production costs (combined with environmental and political considerations) will govern the future transition from the "classical" (high concentration factor) ores to the lower-grade and more difficult to extract sources of tomorrow like oceanic resources, with increased role of recycling.

Keywords: Giant metallic deposits; geochemical mega-accumulations; mineral discovery; metal supplies; history of ore discovery.

1. Introduction

Humanity is obsessed with magnitude and ranking of objects, events and processes with special attention paid to the largest, longest, best or worst examples. This could be accomplished in a subjective way usually based on limited facts blended with emotion and a variety of beliefs as in tabloid newspapers or political pronouncements, or it could be accomplished in a more respectable fashion based on serious quantitative data gathering (e.g. the world's countries, cities, population, income etc. statistics). The magnitude and rank preoccupation is also ubiquitous in geosciences and mining where it sometimes overlaps with classification and organization of objects. In the past hundred years the purely subjectively defined magnitudes underwent gradual quantification driven by increasing abundance of numerical data.

Organized and localized metal mining, as opposed to opportunity collecting of naturally occurring loose pieces of metals like gold, meteoric iron and copper at the surface, goes back mere 9000 years in human history, and this only in few places with advanced ancient civilizations (Hauptmann, 2007). Starting from surface ore outcrop the highly selective mining soon progressed to shallow depth, resulting in a mine. The numbers of mines and intensity of mining fluctuated with politics and economics of the day, increasing in times of high demand for the few "antiquity" metals (Au, Cu, Sn, Ag, later Fe) in time of state- and empire-building periods as in Sumeria (~4000 B.C.), Pharaonic Egypt (3500-2000 B.C.), early China dynasties like Shank, Chou and Han (~1500 B.C. to ~220 A.D.), the Phoenician state (~1000 B.C.), the Athens Republic (Conofagos, 1980) and the Roman Empire (~300 B.C. to ~400 A.D.; Fig. 1.1.). It is estimated that before A.D.1 there were about 20 areas ("districts") of metal mining around the world, complete with benefication and smelting facilities (Aitchinson, 1960). Their numbers kept slowly increasing through the Middle Ages, accelerating after the (re)discovery of the Americas by Europeans, then during the Industrial Revolution, colonialism, modern economic booms (Belich, 2009). Active mine numbers and sizes skyrocketed during two World Wars and afterwards. After the 18th Century the rapidly growing number of mineral discoveries and mine establishment was partly driven by the discovery of new metals, followed by their practical utilization and profitability (Blainey, 1970). It is estimated that there are some 300,000 metallic deposits of some significance in the world mined in the past, at present, or awaiting future development.

From the earliest times the importance of metal mines/deposits or regions was recognized and this recognition became a part of the folklore and published word. Countries and territories with recognized mineral wealth became targets of conquests and non-military acquisitions. But mine importance and fame did not necessarily correspond to deposit sizes: that is, tonnage of contained metal. Some famous deposits of antiquity like Jáchymov (Joachimsthal), the home of the popular 16th Century silver currency called joachimsthaller that later gave us thaller, tolar, eventually dollar, were of the "medium" rank only, based on magnitude terminology discussed below (mere 1,500 t Ag in Jáchymov). Other deposits like Kutná Hora (2500 t Ag) or Freiberg (5000 to 7000 t Ag) were of the "large" magnitude in the terminology of Laznicka (1999), but would qualify as of "World Class", as proposed by Singer (1995), in their particular period (but not now). Only about 20-30 deposits we now know to be of the "giant" magnitude (read below) were known before the year 1750, of which about 15 "Old World" deposits were mined before the re-discovery of the Americas in 1492. After that, the inventory of world's giant deposits (mostly of silver and gold) increased. The scarcity of ancient deposits we now know are of "giant" size was also the consequence of limited inventory of known metals, as only 12 "classical" metals (Au, Ag, Cu, Sn, Fe, Pb +/- Hg, Sb, As, Co, Bi, Zn) were known and utilized before A.D. 1750. The avalanche of discoveries of naturally occurring chemical elements took place between 1750 and 1925, the utilization of which than triggered demand, mining and exploration.

2. Quantitative magnitude and terminology of natural metal accumulations

2.1. Organization

Petroleum industry has been the first to quantify and name magnitudes of hydrocarbon (petroleum and natural gas) reservoirs, with special emphasis on the “giant” and “supergiant” pools. In the United States magnitude terminology “giant oilfield” started at 100 million barrels (=159 x 10^8 litres; Hobson and Tiratsoo, 1981), whereas the international threshold limit for an oil “giant” is 500 million barrels (500 Mbl; Harris and Weber, 2006; Halbouty, ed., 2003). A “giant” gas field contains more than 3 trillion cubic feet of gas (Halbouty, 2003). A specialized literature about the oil and gas “giants” and “supergiants” has gradually evolved and this includes progress reports for successive decades published as the American Association of Petroleum Geologists Memoirs (e.g. Memoir 78 for the Decade 1990-1999; Halbouty, ed., 2003). Based on now “classical” and incomplete data from the 1970s (Hobson and Tiratsoo, 1981) there were 187 “giant” and 17 “supergiant” (over 10 x 1^{10} barrels) oilfields in the world, of which 33 oilfields (about 0.1% of world’s total) accounted for more than a quarter of the estimated ultimately recoverable oil resources of the world. Klett and Schmoker (2003) gathered 1981 through 1996 data for 186 (super) giant fields of the world (minus those in Canada and the United States) and recorded a steady growth in resources. Gradually, resources of hydrocarbons in then “unconventional” and presently “modern” reservoirs such as in “tar sands” and “shales” have been included. The quantitative resource magnitude methodology as developed by the hydrocarbon industry, including the hierarchical organisation of reservoirs, definition of “plays” (=geological settings) and prospectivity evaluations, found later their parallel in the field of geological metal accumulations (ore geology); the latter, however, suffers from a substantially greater complexity because of the much greater number of commodities (metals) and styles of their accumulation (ore deposit types). This complicates the application of the “peak oil” concept bearing on resources exhaustion (Smith, 2012).

Since about the mid-1970s the colloquial word “world-class” deposit became increasingly frequent at technical conferences and in technical literature, eventually invading the research writing. Lacking definition, the world classiness of a deposit was solely in the eyes of the beholder, having no value for comparisons and rankings. Singer (1995) performed quantitative analysis of the U.S. Geological Survey data on world’s deposits of Au, Ag, Cu, Pb and Zn and assigned the “world class” rank to the upper 10 percent deposits in term of contained metals. Although rational, Singer’s classification depends on permanently updated global database for more than the five metals, where the data are a blend of geologic (“natural”) and economic (industrial) factors. Government bureaucracies in socialist countries (former USSR, P.R. China) developed a broad terminology of ore deposit sizes that provided some magnitude approximation in the absence of tonnage figures missing in the secretive official literature. So in China superlarge deposits contain >100 t Au, large 20-100 t, Au medium to small <20 t Au.

2.2. Metal accumulation magnitudes related to mean crustal content of elements

All 92 naturally occurring chemical elements that include metals are present in rocks and terrestrial materials in various but mainly low (near-Clarke) concentrations. Delineated sites where one or more metals form anomalous local, usually highly geochemically concentrated accumulations, have been of economic interest and have been called (classical or normal) ore deposits (or ore fields, districts, etc.). A small number of metal sources utilized by the industry at present, and more so in the future, do not comply with the above definition as their metals may not be anomalously concentrated (approaching Clarke or sub-Clarke values like Mg extracted from sea water or Ti in some low-grade beach and dune sand deposits) or being low-concentration by-products of some higher-concentrated metals or substances (like Au, Ag or PGE in some base metal ores). Furthermore, there are some anomalously concentrated metals in geological materials the accumulations of which are not delineated (do not constitute a "metallic deposit", are open-ended) for various, mostly politico-economic or technologic reasons (like Fe-Mn nodules rich in trace Cu, Co, Ni on the sea floor). The latter then differ from the "classical deposits" and require a different treatment in statistical exercises, especially in comparisons and magnitude rankings. Cathles (2011) proposed a new magnitude unit of 1 Scott=1 Bt of base metals, to accommodate the enormous tonnage of metals in the world ocean interpreted as a single VMS district. What both groupings of natural metal occurrences have in common, however, are their geochemical parameters. Their intensity of geochemical concentration can be expressed in terms of Clarke of concentration (cc; concentration factor) proposed by Fersman (1933) in respect to the mean crustal contents of elements. The magnitude of local metal accumulation and also the intensity of the process(es) that caused such accumulation, can be represented by the tonnage accumulation index (tai; Laznicka, 1986, 1999) obtained by dividing the tonnage of "economic" metal in an ore deposit (e.g. Cu) by Clarke value of the corresponding metal. The resulting figure is the tonnage of the average continental crust that stores amounts of metals equal to the economic deposit where, for copper with Clarke value of 25 ppm, the threshold of a "giant" deposit is 2.5×10^{11} (read below). The latter two variables (cc and tai) are not influenced by politico-economic considerations and they make it possible to compare and rank accumulations of metals with highly contrasting Clarke values (like Fe, Cu and Au) in purely geochemical terms, for example to evaluate efficacy of ore forming systems. This approach is objective, although influenced by the authority whose element abundance values are employed (here we use trace element values for bulk continental crust of Wedepohl,1995), as there are often major discrepancies among several authorities who recently published their estimates of continental crust Clarke values (Palme and O'Neill, 2004; Taylor and McLennan, 1995; Rudnick and Gao, 2004). Alternatively, accumulations of "economic" metals in ore deposits can be related to trace metals means in granites, shales, the oceanic crust, mantle, chondrites and others. Table 2-1 is the proposed magnitude terminology of metallic deposits. Table 2-2 lists thresholds and ranges of the giant and super-giant deposits of 40 metals. The magnitude limits used here represent no qualitative breaks in the geological character of metallic deposits where the "ore giants" are just the magnitude peaks in the series of increasingly larger deposits of the same type (Fig. 2-1). In this paper the concept of ore giants has been applied mainly to rationally select the number of ore deposits to be compared (915) out of the estimated minimum of some 300,000 global database entries of metallic deposits that have been mined or explored. Major deposits of some metals like aluminium stay outside the "giants" concept because their Clarke values are too high, requiring exceptional deposit sizes that do not yet exist while bauxite is the only practical Al source. Several low demand, yet geochemically relatively abundant metals like Ga, Ge, Sc, Tl also lack giant deposit entries because of insufficient economic incentive to go and explore. Despite this, significant deposits of the "non-giant" metals are also considered here.

2.3. The database

Quantitative definitions, organizations and magnitude comparisons of metallic deposits can only be attempted when a sufficient population of numerical data, in particular ore and contained metal tonnages and grades, become available. Until about 100 years ago only fragmentary data on some deposits entered the records and literature, and most such data were variously expressed as monetary yields in ancient currencies or weights that required laborious and uncertain conversion to uniform present day values. Moreover, all such data were historical accumulations of production or sales figures from deposits economic in the period (mostly high-grade vein or placer deposits with coarse, uniform minerals easy to manually separate). Reliable data on ore reserves resulting from pre-mining exploration, in mined deposits combined with past production records, started to appear only in the late 1800s and especially early 1900s, with the onset of bulk production from open pits of what were then "low-grade" ores,. Most reliable production/reserve figures in the first half of the 20 Century originated and were published in the United States (Lindgren and Laughlin, 1919; Emmons et al., 1927) and they found their way into economic geology textbooks of the period (Emmons 1937; Lindgren, 1933). Although by 1950 it was possible to tabulate quantitative data for several hundred prominent deposits of the world, the process was greatly accelerated with the advent of computerization and availability of database software like dBASE, Microsoft Access and Excel in the 1960s and beyond. Several early quantitative databases of national, regional or world's resources in public domain (e.g. MANIFILE, Laznicka 1973) treated all deposits regardless of size, although it was easy to electronically retrieve those of exceptional magnitude. The inventory of databases of metallic deposits, national (e.g. Long et al., 2000; Ewers et al., 2002), continental (e.g. BRGM-CIGCES, 2004) and global (Mason and Arndt, 1996) has greatly increased in the past 30 years. The databases cover selected groups of deposits (e.g. porphyry copper deposits, Mutschler et al., 2000; Singer et al., 2002, 2008) all deposits of some metals (Cu: Kirkham and Raefer, 2003; Au in the C.I.S., Levitan 2008) and all deposits everywhere (www.mrdata.usgs.gov; U.S. Geological Survey, 2008). The annual Minerals Yearbook publication of the U.S. Geological Survey (available free on-line) provides up-to-date information about global developments in metals supplies (not much about geology!), and there is a large amount of information about geological sources of metals as well and non-metallic minerals in the work of Dill (2010).

The completeness of databases, in the present study reflected in the number of “giant” deposits captured, depends on information availability, especially of the quantitative data like location coordinates, deposit dimensions, tonnage and grade. The information is sourced from published and some archival literature, company reports, oral communication and, in the past 20 years, from government and company websites. The number of entries in databases of “ore giants” have rapidly grown in the past 50 years not only by addition of newly discovered and enlarged existing deposits, but also by declassification of quantitative information previously considered confidential and missing from official publications (Laznicka, 1985b). The greatest “emasculation” of previously numberless “giants” took place in the 1990s following the demise of the Soviet Union, that resulted in partial liberalization of quantitative information flow from Russia and C.I.S., China, Mongolia, Vietnam and Eastern Europe.

2.1.1. The nature of quantitative data on ore deposits

Ore deposits and their hierarchically higher groupings (ore clusters, fields, districts, belts, etc.) are local geochemical accumulations of metals that have been delineated in space and defined in terms of ore tonnage and metal concentration (=grade). The quoted (or assumed) grade is a mean or average and for deposits with low ore/waste contrast a cut-off grade is also needed as it influences the ore tonnage and metal average grade. The standard database entries suitable for metallogenic (=macro-geochemical) considerations are ore tonnages with grades as they were before the mining has started (pre-mining resources; metal endowment). Ideal tonnage figures approximately correspond to the “resource base” of the U.S. Geological Survey and are most reliable for newly discovered pristine deposits. However, even the most accurate ore metal quantities are influenced by the average and cutoff grades that are rarely identified in the secondary literature. For example, the Agua Rica (Argentina) resources quoted by Landtwing et al. (2002) could enter a database as either 4.65 Mt Cu at 0.4% Cu cutoff, or as 7.37 Mt Cu at 0.2% Cu cutoff, a 158 % discrepancy! Near-equivalent of pre-mining resources can be produced by adding ore/metal tonnages of past production and remaining reserves, when known. In the present database the more reliable metal tonnage figures include past production and/or new reserves and resources including inferred resources if considered reliable and respectable. Unfortunately, a large proportion of published quantitative information is fragmentary, incomplete or obsolete (for example, recent reserves of a mature mine only, or past production for a period of time) and, moreover, the tonnage/grade figures quoted in the general literature (especially in research papers) are rarely qualified as to what they really represent. This is further complicated by the rapid tonnage creep of metal endowments in active mines or prospects (Fig. 2-2). Mudd et al. (2013) expressed similar sentiments about the nature of the available quantitative ore information.

Uncertainty about the nature of mine data is the source of frequent discrepancy in the quantitative figures quoted in the literature, often in the same publication. For example, the metal endowment in Peschanka, Russia, is quoted as 27 Mt Cu and 1,600 t Au in SEG Newsletter No. 89, 2012, but as 7.9 Mt Cu, 450 t Au half a year later, in Issue 91!. As a consequence all tonnage data quoted here as well as in the source publications should be considered as approximate only, regardless of the apparent numerical accuracy. This limitation applies to other quantities quoted in the literature as well, like radiometric ages, analytical data and compilations such as mean crustal contents, geographical information like coordinates and distances, ore discovery dates and others. Most discrepancies are limited to one order of magnitude with data reliability about plus/minus 20%, but extreme discrepancies do exist. Some metals in ores, considered undesirable, have to pass through the benefication process to extract the principal metal (typically gold), but are not marketed and have to be disposed off. At the huge Olimpiada deposit in Siberia the refractory hypogene ore contains 0.2-0.35% As and ~0.35% Sb (Wardell Armstrong, 2011), making Olimpiada an As+Sb "giant". This, however, is rarely publicized because of the negative stigma of toxicity so, with 450 Mt resource @ 3.3 g/t Au (www.polyusgold.com) the minimal endowment there would be about 1.125 Mt As and 900 Kt Sb! A genuine "triple giant" (Au, As, Sb) indeed.

The metal quantity entries quantified and compared in the present study are local accumulations of a single metal. Although most listed entries represent deposits with a single major metal accumulation (e.g. of Cu), some deposits contain "giant" quantities of two or more metals (for example, Olympic Dam is a multiple "giant" of Cu, U, Au, Ag and REE). Such deposits have two or more database entries (Table 2-3).

The reliability of metal endowment data and their suitability for applications in metallogeny, and the conclusions reached, are further reduced by mixing of the various size and complexity categories of metal-bearing objects. An ideal "deposit" should be a single, continuously mineralized delineated metal accumulation like Olympic Dam (plane projection 6x3 km). Even so, there are several varieties of ore with slightly different setting, metals content, and other properties within this deposit. Deposits composed of coalescing ore lenses as in Broken Hill, NSW or Mount Isa, or composite orebodies of two or more ore styles resulting from a single genetic system like the lens and stem VMS deposits, should also qualify as single database entries. Groups of deposits (clusters, ore fields, districts) should be clearly identified in quantitative comparisons. The Upper Mississippi Valley "district" (Heyl et al., 1959) is an area of 7,800 km^2 in three U.S. states that contains 400 individual deposits, none of them of giant size. Even worse, it is unrealistic to treat the Witwatersrand, a 470 x 250 km "basin" with seven separate "goldfields", each with a number of "reefs" (orebodies), as one "deposit", at par with a single deposit like Muruntau, in quantitative exercises without a clear notification. This approach is unfortunately common in the literature and at conference presentations. It distorts the metallogenic conclusions reached.

2.4. Dimension and complexity of metal accumulations

Table 2-4 and Figure 2-3 represent selected examples of "ore giant" database entries arranged by their dimension in outcrop or subcrop ("footprint"). Six orders of dimensional magnitude (from 100 m to 100,000 km) are individually numbered from 1 to 6, and these numbers appear in various tables throughout this study. The terminology based on dimension and complexity of mineralized objects in the literature is non-uniform, inexact, overlapping and applied subjectively. The progression from the smallest and simplest ore objects starts with orebody (or "ore shoot"), an internally uniform delineated metal accumulation. The usual dimension of orebodies is between about 100m and 5 km, although some ore beds or layers can continue, with little change, for almost 100 km (80 km for the Rustenburg segment of the Merensky Reef). An orebody can overlap in size with an internally uniform ore deposit (marked "u" in Table 2-4), although many deposits comprise several ore varieties (marked "d"). These varieties could be broadly syndepositional as with the lens/mound and stem/feeder VMS deposits, or skarn, hi-sulfidation members associated with a porphyry-Cu systems. Alternatively, different ore styles can result from post-depositional superimposed modifications of earlier deposits (code "s"), as with gossans, oxidation zones, supergene enriched zones or physically reworked ores.

Groupings of separate orebodies or deposits in an area between about 5 and 30 km in diameter can best be described as clusters (alternatively "ore fields", e.g. goldfields or the Russian "ore knots") or, if larger (between about 20 and 60 km), as districts. The term "district" is also used as an administrative division with limited relationship to geology and so are the purely production or proprietary terms mine or property, each of which can contain more than one deposit or, in turn, share a portion of a continuous deposit with others. Equidimensional (e.g. circular) or irregular clusters or districts are designated "e" here (Table 2-4); this and the higher-up equidimensional categories also include "basins" (e.g. the Witwatersrand) and magmatic complexes (e.g. Sudbury). Linear deposits groupings (typically fault controlled) are called belts (e.g. a metal belt like Cu-belt; ”L”=linear belts grade to “S”, semi-linear metal areas in Table 2-4). The length of mineralized “belts”, as used in the literature, ranges from hundreds of meters to thousands of kilometres; a mini-belt on deposit-cluster scale, here called “zone”, measures between several km to about 30-50 km; meso-belts (also termed “trends”) on district to small regional scale measure between about 20 and 150 km. Mega-belts are continental or even multicontinental (e.g. the Circum-Pacific copper belt) and they measure from hundreds to tens of thousands kilometres. Large geological regions dominated by deposits of one or more metals, usually of a distinct style, are called provinces (Turneaure, 1955; Bilibin, 1976). These are highly subjective. Internally the clusters, districts, basins, belts and provinces could be uniform (ideally containing deposits of the same metal, same age, same or related style like porphyry Cu-belts; “u” in Table 2-4), or nonuniform, of mixed populations of metals, scales and ages (“m” in Table 2-4).

3. Characteristics of giant metal accumulations (“deposits”)

3.1. Classical metallic deposits

As of now, there are 1171 giant and 137 supergiant (total 1,308) metal accumulations representing 915 “deposits” (some “deposits” have two or more giant metal accumulations) and low-rank groupings (clusters, some “districts”, several “areas” and “basins”) of 32 metals and metals groups (REE, PGE; Figure 3-1, Table 3-1): an increase of 139 % against the 486 giant and 61 super-giant numbers included in Laznicka (1999) and representative of the state of the earlier database. The earlier database included quantitative entries that were in public domain through the mid-1990s. The substantial increase in the number of “giants” since is only partly due to new discoveries, resources growth at existing deposits and/or discovery announcements, although there has been a major increase in exploration activity after 2003 with the rise of commodity prices. Many “new” database entries are the result of delayed release of previously confidential quantitative data about “old” deposits in the USSR, China and other socialist countries following the political changes and reduction of information secrecy in the 1990s. This data release still gradually continues and is not yet complete.

Table 3-2 is a compilation of the largest presently economic (“industrial”) geological accumulations of metals, primarily intended as a basis for further discussion. The selection of entries is partly subjective, as one can manipulate “giant” accumulations as collective entries (that include more than one orebody/deposit) by using various configurations-this seems to be a standard practice in lists published in the literature. It appears that single delineated continuous deposits are in the minority in most lists. Whenever possible, mega-entries (like the

Witwatersrand "Basin") have been here substituted by lesser magnitude constituents, in this case "goldfields". This, however, has not been practical in some cases, so the "Central African Copperbelt" cobalt entry is the cumulative Co tonnage from a number of individual deposits.

The entries ("deposits") in Table 3-2 are dominated by "classical deposits" (with high geochemical concentration factors) that are presently mined, were mined in the past, or are suitable for exploitation in the near future. Unconventional metal accumulations, many of which are open-ended (not delineated) and largely speculative, are reviewed below, as many will become resources of the future. As all the information came from published, internet and some oral communication sources it could have absorbed errors in fact and quantities. Particularly common in the literature are metal tonnage errors due to confusion in decimals-e.g.100 Kt deposit presented as 1 Mt and vice versa. Some published tonnage figures are suspect (e.g. the 5.2 Bt Fe Musan skarn in North Korea for which I have not found confirmation, listed in Meinert et al., 2005; the 200 Kt Be and 300 Kt Bi in Shizhouyuan, Hunan; the 6 Mt Cu in Gejiu) and other. Quoted tonnages change (mostly grow) rapidly with time and mining / exploration progress.

The purpose of Table 3-2 is not to present a permanent magnitude ranking but rather a presentation of cases where a local metal accumulation has been exceptional, so that the geological/geochemical causes could be investigated and hopefully explained. To do so, however, requires that the politico-economic causes that strongly influence most ore discoveries and utilization be recognized and when necessary excluded from purely "natural" considerations (Fig. 3.2). The enormous relative tonnages of some metals (e.g. Au, Cu) and vitality of recent discoveries as listed in Table 3-2 and treated more thoroughly in Section 5, contrast strongly with feeble tonnages of other metals like Hg, As, Cd that virtually lack major new discoveries in the past 50 years (unless where metals like As are associated with the more desirable metals like Au). Demand and price drive exploration and when the former are low or non-existent no new discoveries are made, unless by accident. In the past 50 years, the exploration emphasis and resulting discoveries followed a progression from the economically most desirable to the least desirable metals, or from metals with sufficiently known existing resources to those with growing new demand, as follows: Au, Cu > Ag, PGE (U, Fe, Li, REE, Ta, Ni, Be, Ge) > Zn, Pb (Al. Mg, Co, Ti, Zr) > Mo, W, Sn, Bi, Mn, Nb (Re, Sc) > Sb, Th, Y >> As, Hg, Cd, Tl. The metals in brackets experienced sudden and often temporary boosts or strong fluctuation in demand that accelerated or decelerated exploration. For example, the uranium peak demand for military purposes in the 1940s-1950s and frantic search rapidly subsided afterwards, to return with renewed demand during the construction of nuclear power plants in the 1960s and 1970s, subsequently reduced by several widely publicized mishaps (e.g. Chornobil in 1986). The demand for U and its price revival in the 2000s has most recently been interrupted by the Fukushima catastrophe in 2011. Ta, REE and Li gained by sudden demand triggered by development of new products like cell phones in the 1990s (Ta) and electric cars (2000s; Li), and this was followed by new discoveries of deposits or renewed exploration of long known deposits or occurrences that added a number of “giants” to the database (e.g. the Li in brine or hectorite deposits; the ion-absorption clays for heavy rare earths in China).

Some global inventories of metals have an excess capacity and the confirmed resources are sufficient for many years (e.g. the 69.2 Mt Nb inventory would cover the present world consumption for 1098 years) so that there is no incentive to find more (Table 3-1). Sometimes this logic does not apply. There is about 67.2 Mt of Mo world inventory, sufficient for 269 years at present consumption, accumulated partly inadvertently during exploration for porphyry Cu deposits, most of which have a Mo co-product (the largest Mo super-giant accumulations are now in porphyry-Cu deposits-e.g.8.51 Mt Mo is in the Chuquicamata zone). Yet Mo is still explored for and there are several development projects under way (e.g. Mount Hope, Nevada; Unicorn, Victoria; Merlin, Queensland; a large number of Mo deposits in China). Some metals of moderate or steady demand sourced from several long known deposits (e.g. Al, Mn) or where metal supply was dominated by one or few deposits (e.g. Araxá for Nb, Bayan Obo for REE) generated little exploration interest unless political decisions changed the status quo. So in the early 2010s when China restricted their rare earths exports, a frantic exploration has ensued leading to revitalization of some long known deposits (e.g. Mount Weld) and reopening of closed mines (Mountain Pass), although few major “greenfield” discoveries have, so far, been made. Thorium, a long neglected metal without a single dedicated mine anywhere in the world and with limited production sourced from by-products (mostly of processing monazite for REE, itself a by-product of heavy minerals from beach sands mined mostly for Ti in ilmenite and rutile, and zircon), seems to be growing into a desirable commodity to fuel a new generation of safer and more economical nuclear power plants (e.g. www.thoriumenergy.com; www.reeminerals.no; U.S. Geological Survey Minerals Yearbooks on-line). The usual first step in metal’s ascendancy is a national and international inventarization of known and potential resources so, of the 2010 global inventory of 2.61 Mt Th (USGS data) the bulk is in monazite (12 Mt identified global resource), virtually all from beach sands (monazites from carbonatite and Bayan Obo-style metasomatites are low in Th). The India Ministry of State identified a national resource of 11.93 Mt of beach sand monazite, most of it in the hitherto little publicized eastern coast beaches in Orissa, Andhra and Tamil Nadu rather than in the long-known “black sands” of Kerala.

As, Hg, Cd, partly Pb, Sb and Be have recently been on the loosing demand side as a consequence of, at times paranoid, concerns about toxicity by the risk averse population of the developed countries and their governments. This virtually cancelled exploration for new deposits of the “villain” metals and closure of the existing ones. The costs of reclamation and disposal of toxic by-product metals (paid for mostly by governments) greatly exceeds any potential benefits of metal exploitation. Toxicity/disposal problems have retarded or entirely cancelled development of several deposits where a toxic metal accompanies a desirable metal like As in some Au deposits (e.g. Vasil'kovskoe in Kazakhstan-an Au giant, Rakkejaur in Sweden or Mokrsko in Czech Republic-not "giants"). The public apprehension is particularly strong in case of uranium as in Australia, where the public opinion would not allow development of nuclear power plants despite the country having some 35-40% of presently economic world U resources. In unified Germany, the former largest East German uranium deposit Ronneburg was reclaimed, leaving close to 100 Kt U in ground (Fig. 3.3). So the politico-economic factors are strongly influencing the metallogeny (macro-geochemistry) of exceptional metal accumulations although this does not happen in a uniform way and every case has to be considered individually.

Commodity (metal) prices provide a quantitative measure of the political-economic conditions that influence exploration and mining which, in turn, distort the results of quantitative considerations when the "mine" data are applied to metallogenic analysis. In general, metal prices are broadly proportional to trace metal abundances as expressed by Clarke values (prices of Au >> Cu >> Fe); however, some metals (e.g. Ti, REE, Ga) are relatively "overpriced" in respect to their Clarkes, others are "underpriced" (e.g. Sb, As, Hg; see graph in Laznicka, 1983). Other than for industrial demand, this is caused by the variable cost of extraction (for example, metallic Ti > Al > Fe) and marketable products (e.g. Ti metal is more expensive that TiO_2 pigment), but also the geochemical ability of some metals to locally super-concentrate: that is, form numerous deposits with very high concentration factors. This may be one of the reasons why Pb (average grade about 4-5%, Clarke 16 ppm) and Sb (average grade about 2-3%, Clarke 0.3 ppm) are relatively "cheap" despite the very high Clarkes of concentration (about 2,800 and 83,000, respectively). Metal prices have an abundant specialized literature (e.g. in the U.S. Geological Survey Minerals Yearbooks at minerals.usgs.gov/minerals/pubs/myb.html; in Crowson, 1998 and subsequent yearly issues) but need to be used with care in support of metallogenic conclusions.

3.2. Unconventional, mostly non-delineated metal resources of the future

Once the "classical" (highly concentrated) deposits are mined-out and not replenished by new discoveries both in outcrop and under cover, the world will have to move to alternative metal sources to keep or even increase its present standard of living. Clearly, the substitute resources will have lower to much lower metal grades, will require new mining and processing technology, will have a more difficult access, more costly recovery and there will be an increased environmental damage as lower grade will mean greater tonnage of material to be mined, processed, then the waste stored. This future trend is already here: the steadily decreasing ore grades (e.g. from an average of about 6 g/t Au in the 1960s' to the present ~3 g/t in hard-rock deposits, with cutoffs as low as 0.1 g/t Au) will soon convert yesterday's protores to today's ores (like non-enriched iron ores with 16 % Fe in Kachkanar) and the day is not far away when "ordinary rocks" will be mined as a source of Mg, Cr and Ni (from ultrabasic rocks), Al (from clays, anorthosite or nepheline syenite), or Fe (from low-grade beach sands or iron formations). This era has already started, although on a small scale: Monto Mines in Queensland started to recover ilmenite from gabbro and its regolith, to compete with the same product derived more cheaply from beach sands that do not require crushing. Some metal contents in easy to mine and process materials like beach and dune sands now have metal grades lower than the Clarke values of corresponding metals (e.g. 0.3 % Ti in the dune sand mined at Stradbrooke Island off Brisbane in Queensland that is lower than the 0.4 % Ti crustal Clarke) and, of course, the recovery of metallic magnesium from sea water with 0.13% Mg (Mg Clarke = 1.95%). But the above materials still account for less than 1% of metals recovered worldwide. This is to change, probably soon.

The U.S. Geological Survey, and some other State Surveys, maintain programs designed to inventorize and predict undiscovered mineral resources (e.g. USGS Minerals Team, 1996). These programs, many of which use the Gallup Poll methodology to quantify the subjective opinions of "experts", target the types of "classical" ore deposits that are mined today, for example porphyry-Cu deposits. The future, very low-grade to sub-Clarke resources that are different are usually not considered, although many are already known but have not been delineated, hence the metal endowment estimates are very inaccurate. Also, viable mining and processing technologies are not yet available or have not been sufficiently tested. There are also numerous political problems bearing on exploitation to be overcome. Collectively, however, there are enormous amounts of metals to be won in the future from the known nonconventional sources that are not only capable of replenishment of metal supplies lost with the demise of exhausted deposits, but that could exceed the historical world production many times over (Cathles, 2010). Some, like metals to be extracted from sea water, are virtually inexhaustible.Table 3-3 lists examples of the presently known unconventional metal resources, together with the number of estimated supply years, at the present rate of consumption. These resources fall into several categories:

--Presently recoverable (Mg) and potentially recoverable (e.g. U, Au, Li) metals dissolved in sea water;

--Ocean floor resources, dominated in terms of viability by the Fe-Mn nodules, followed by Mn crusts and metalliferous clays. The main recoverable metals are Mn > Ni, Cu, Co > Zn, Mo, V, REE and others;

--elevated trace metals in large tonnage commodities mined for another product, that could be recovered as a by-product like phosphorite deposits that, especially in the Florida-Georgia

province and in Morocco, collectively store more than 10 Mt U. Although some uranium has been, and is being, recovered, the recovery is not systematic and can be much improved.
--elevated trace metals in selected intervals of rock units (e.g. carbonaceous pelites like the Bazhenov Formation of Siberia; the Alum Shale of Sweden), or petrographic varieties with regular complement of trace metals enriched, in respect to crustal Clarke, by two or three orders of magnitude (e.g. ultrabasic rocks for Cr, Ni, Mg; alkaline rocks and carbonatites for Zr, Nb, Ta, REE, Th and others);
--waste products resulting from ore benefication (e.g. Ga from bauxite red muds), or imperfectly processed tailings from past operations, especially gold. At present, a significant portion of gold coming from the Witwatersrand is sourced from reprocessing of earlier tailings.

The metal tonnages quoted in the literature, or calculated by the present author, are highly inaccurate but even the lowest figures quoted for some metals (e.g. Co, Mn, Mo, U, V, Zn) are more than sufficient to assure supply security for many centuries to come, especially when the ocean floor resources are tapped (Cathles, 2010; this does not consider the politico-economic obstacles to development). Some other metals, however, would have to be sourced from "rocks", or humanity will have to reduce growth, consumption, or resort to substitutes.

How does this relate to the concept of giant deposits, and what magnitude terminology to use? Clearly, if any of the unconventional resources is ever accurately delineated and the metal endowment enumerated, the resulting metal quantities will exceed the present super-giant category (10^{12} in respect to Clarke values) many times over, resulting in super-super-giant and higher categories; for example the uranium stored in the Bazhenov Shale (Gavshin and Zakharov, 1996) of 6 billion tons U will fall into the 10^{15} category! (This spectacular resource, if the endowment figures are correct, is a siliceous argillite with 8% of organic carbon, in depth of 2-3 km under Khanty-Mansijsk region in the West Siberian Basin, Russia. The Late Jurassic-Early Cretaceous metalliferous horizon is between 6 and 21 m thick, stores 18 trillion tons of organic matter, and billions tons of Mo, V and Zn in addition to U). Should future mining of extensive, continuous, non-delineated resources like the oceanic Fe-Mn nodules or clays ever take place, the areas will likely be subdivided into properties (as is the case today with the Bushveld platiniferous reefs that are a single orebody continuous for hundreds of kilometres), with the metal endowment reported separately for each.

Although some of the slightly super-Clarke materials are not yet economically exploited by humanity, some may have acted as "source beds" to the higher-grade traditional ores in the geological past. This is discussed in more detail below in connection with the metal accumulating systems.

4. Giant metallic deposits as a product of best optimized ore forming systems

4.1. How metallic deposits form

A “classical” ore deposit (or a hierarchically higher division like district or belt) is a local anomalous geological metal accumulation that is, was, or will likely be economic: that is, profitable to mine and process to yield a marketable product, typically a metal. A number of definitions of an “ore deposit” have been advanced, none being absolutely inclusive as there are always exceptions, transitions, variations. What is important to note is that we are dealing with sites of accumulation of geological materials (metals) that also have to comply with economic, politico-economic and technological parameters and expectations that may change with time. The discipline of Economic Geology deals with a selection of localized geological objects that are in some way unique and anomalous in respect to the “normal rocks” (or aggregates, liquids, gases); in most cases the anomalism is geochemical (large local accumulations of highly concentrated metals), but also textural or structural (e.g. deposits of chrysotile asbestos geochemically indistinguishable from their ultrabasic rock parents). The “rocks” or aggregates themselves that are not geochemically exceptional could also constitute economic deposits (e.g. of sand and gravel, building stone) and here the physical properties and location, among others, are the main parameters of profitability. In this paper the two latter categories of economic materials are not considered and the conclusions are entirely based on accumulations of the “ore metals”, especially in the “classical” (=delineated, high-metal concentration) deposits.

Metals are chemical elements so their distribution and fluxes in the Earth’s materials is studied by geochemistry (Clarke and Washington, 1924; Goldschmidt, 1933, 1958; Fersman,1933). Métallogenie (de:Launay, 1913), usually expressed in English as metallogeny or metallogenesis, is a geochemistry applied to anomalous metal accumulations and concentrations, combined with other geological aspects like structure and geodynamics, where the selection of its members is often influenced by economic considerations. The super-anomalous local metal accumulations may constitute the “ore giants”, as treated here. The formation of giant deposits is thus a successful terminal super-product of a usually protracted set of geochemical developments that should be considered in its “pure” form, divorced of the “noise” of economics and politics. This purpose is served by the magnitude organization of ore-bearing objects as related to mean crustal contents of metals (Laznicka, 1986, 2010; read above).

There are two end-member mechanisms that can produce local highly concentrated, large tonnage accumulations of metals: 1) Instant, or short duration events that bring in metals in already highly concentrated, ore-grade form; 2) Protracted sets of processes of incremental metal concentration and accumulation, followed by conservation to preserve the orebody until the moment of exploitation, in a reasonably accessible site.

1) "Instant" metal accumulations. Except for human activities of local metal hoarding like stockpiles, recycling or the gold in Fort Knox, there are only two possible repositories of preconcentrated metals available for import: the Earth interior, especially the Fe-Ni core, and the outer space, especially the asteroids. Metals derived from the core have been nowhere identified. The native iron in the Disko Island basaltic dikes (Fundal, 1975), formerly interpreted by some as brought in from "the Earth interior", has been since convincingly interpreted as of local, terrestrial origin. The outer space origin of high-grade metals like Fe+Ni and platinum group elements in chondrites is real, repeatedly confirmed by observed meteorite falls. Unfortunately, the meteoritic "ore" tonnages preserved on Earth are miniscule, although more is believed present in asteroids (Bush, 2006). The only "giant" metal accumulation, ever suggested to be of possible cosmogenic origin (Dietz, 1972; Morrison, 1984) is in the Ni-Cu-PGE sulfidic ores in Sudbury, Ontario, by now convincingly proven to have separated from an impact melt of local provenance during the 1.85 Ga Sudbury event (Prevec and Cawthorn, 2002).

2) Incremental metal accumulation. We can now accept the thesis that all terrestrial metallic deposits are products of local accumulation of metals formerly dispersed, in trace quantities, in rocks, melts and waters within the lithosphere (especially the continental crust) and hydrosphere, and to a lesser extent (but ultimately) in the mantle.

4.2. Geological systems resulting in local metal accumulation

In the past thirty years or so it has become increasingly common to treat formation of mineral deposits in terms of multicomponental systems, an all-inclusive approach and an improvement on the earlier one-sided emphasis and classifications. An ore-forming system is a set of processes, conditions and settings the end product of which is a mineral (metallic) deposit. Ideally, the term system should be restricted to the active set of events that terminates when an orebody is formed. In practice, however, most writers refer to the present occurrence of mineralized objects formed in geological past as a "system", although in reality this is a product of a fossil system, variously subsequently modified by post-depositional events often beyond recognition, and preserved at, or near, the present erosional surface. Such a material relic of a former system, that should more correctly be referred to as a metallogenetic product or an inventory (metallogene), can no longer be explained "beyond reasonable doubt" by direct evidence as is the case with, for example, placer, lateritic (Figure 4.1) or VMS deposits that can be observed and measured while actively forming on land or on the sea floor today, hence the past system has to be interpreted. Most interpretations are conflicting and change with time; they account for thousands of journal pages crowded with analytical results that allow multiplicity of genetic interpretations and system flowcharts.

Successful natural (geological) ore-forming systems that actually result in major metal accumulation are exceedingly rare. They are the product of “fortuitous encounters” (synergy) among trace metal fluxes and their environment that contrast with the “regular” petrogenesis that produces relatively petrographically and geochemically uniform rock varieties distributed over large areas or within large bodies, with expected regularity. Metallic deposits are akin to local deviations (abberations) of the prevalent development and in most cases accommodate metals that failed to remain in their parent rocks in trace quantities. The research results in “rock” petrogenesis and geochemistry, although an essential first step to understand the medium and setting within which anomalous metal accumulations form and reside, are not sufficient to explain the spotty occurrence of many ore deposits. The continuous, mappable tracts of generally uniform rock associations resulting from a geodynamic mega-system like subduction (andesitic and equivalent plutonic magmatic fronts) contain less than 0.01% by volume of potentially economic metal accumulations (e.g. porphyry copper deposits). So special conditions were required to form the ores, one step above the rock-forming mechanism.

The existing ore deposits are clearly a product of former systems. The “chaotic” natural ore-forming systems can best be imagined and understood by comparison with engineered industrial technologies of metal extraction from ores (or other materials like sea water) that are also incremental, starting with lower metal concentrated input to deliver higher concentrated, or “ultimate” (99.9% of metal), output (Table 4.1 and Figure 4.2).

Both engineered and natural incremental systems result in gradual increase of metal concentration and local accumulation with each positive step (stage). This is quite rare in nature where negative increments cancel the previously achieved metal concentration so no orebody results. Most components of an ore-forming system have a number of sub-components, different starting points, and a sequence of stages: for example, interpretation of a porphyry Cu system can start from the moment of fluid separation from cooling intrusion cupola high in the crust, from the moment of subducting slab melting in depth, or from the moment of oceanic crust generation at a spreading ridge. Any extension of a system origin back into the history becomes more speculative, hypothetical, and influenced by the groupthink of the day.

Most metallic deposits are the result of interaction of several components of various “strength” in a favourable setting. A variety of genetic models have been developed since the study of mineral deposits (economic geology) had been born as a branch of geological sciences some 150 years ago. There has been a tendency to focus on the most obvious (leading) component of the ore-forming process referred to as “controls” (e.g. structural control, stratigraphic control), although one control alone would not make an orebody; the majority of brittle faults, a favourite structural control, are devoid of ores although a minority is richly mineralized and/or is a component of more than two thirds of ore forming models. The magnitude of the metal accumulation is proportional to the efficiency of the whole system, and its setting. Sillitoe (2010) pointed out that among most magmatic arc terrains capable to host porphyry Cu or Au, over 90% of identified former systems lack economic mineralization because of insufficient optimization, like absence or poor development of some critical steps in the mineralization sequence. Vry et al. (2010) argued that the super-giant El Teniente Cu deposit, qualitatively a rather “normal” porphyry-Cu, owes its huge size (128 Mt Cu) to subduction of a spreading ridge; effective entrapment lithology of a mafic complex in roof of mineralizing intrusions; brittle fracturing and chemical entrapment capability of the ore hosts; multiplicity of successive intrusion pulses, each with its own mineralized carapace breccia; lack of barren intermineral porphyries to dilute the orebody (but a late stage explosion breccia pipe that removed and dissipated a portion of the previously formed ore); a long-lived underlying magma chamber. In non-engineered geological ore systems the best optima are rarely achieved so the presence of a major deposit cannot be mathematically predicted, although some authors have tried (Singer et al., 2005; Cunningham et al., 2007; Guj et al., 2011).

Cooke et al. (2005) selected six exploration indicators that may characterize magmatic arcs that are more suitable than the rest to include giant porphyry deposits, starting with the premineralization architecture conditioned by extensional tectonics (Gow and Walshe, 2005). Kerrich et al. (2000), Groves et al. (2003) and Sillitoe (2008) analysed the terrain and genetic characteristics most often associated with giant gold deposits: both in magmatic arcs and in metamorphic belts.

4.3. Components of an ore system

Ore systems, “system types” (Huston et al., 2006), exploration models are defined by their geological setting (“play” of petroleum geologists, “geosite” of Laznicka, 2001) in which the metals concentration and accumulation take place on one hand, and by a set of processes that produce the orebody, on the other hand; both components overlap. Clark (1993) refers to the former conditions as metallogenic or environmental, to the latter as genetic or anatomic. The most often recognized components of an incremental ore-forming system are: i) metal sources; ii) release of trace metals from source followed by metals outflow, transport and increase in concentration. This also requires consideration of the driving energy source and intensity, pressure-temperature considerations, source and nature of fluids, and others; iii) transport of metals to the final site of ore deposition; this involves avenues of transport like permeable faults or porous horizons, nature and volume of fluids, speciation of metals in fluids; iv) the ore site and mechanism of ore precipitation (future ore deposit): voids, pores, replaceable rocks, receptive floor of sedimentary basins; agents causing precipitation like boiling, cooling, oxidation or reduction, fluid mixing, sulfurization; v) preservation of ore accumulations once formed. Ore deposit produced is proportional to the effectiveness of the entire progression moving in the positive direction, but certain components may be more prominent or “visible” than others in formation of the various types of ore deposits; this influenced to a considerable degree the classifications and teaching of “classical” economic geology. Giant metal accumulations are the product of the best optimized interplay of system components that are not different from those that have produced lesser, even embryonal occurrences of the same ore type (Clark, 1993; Richards, 2003; Cooke et al., 2005). From the premise of an exploration geologist the most important ingredients of ore search are the field (or drill core) visual indicators of possible ore presence of a certain type, incorporated into a realistic model (Sillitoe, 2010); no model can, however, predict the magnitude of the expected ore discovery (Fig. 4.3.).

Huston et al. (2006) and other papers in the Economic Geology Number 6, Volume 101 issue devoted to Australian “basinal” Zn-Pb-Ag deposits, developed a likely scenario responsible for the formation of at least five “ore giants” in North-Eastern Australia, and they systematically evaluated components of the obviously exceptionally optimized mineralization systems. The process was initiated by formation of intracratonic grabens subsequently filled by immature clastic sediment during the rifting stage, then covered by sag-stage sediments. Basinal brines moving along faults heated to about 200^{o} C in depth of around 10 km leached trace metals from immature clastic sediments and rift-related volcanic rocks when present. The metal-rich brines returned to the surface following uplift and precipitated metals at the sea floor or in unconsolidated bottom sediments by fluid mixing, cooling, sulfurization or reduction. The exceptional metal endowment of 68.7 Mt Zn, 33 Mt Pb and 58,510 t Ag in four Mount Isa-type deposits resulted from high overall efficiency of the entire system, with no single component credited with a special contribution. Interestingly, there are very few lesser magnitude Zn-Pb deposits in the region (with exception of a cluster of small vein deposits in the Lawn Hill district).

4.4. The progression from “rock” to “ore” as an aid to prospectivity evaluation of terrains

A very small proportion of ore metals that are initially dispersed in a geological domain in trace, as well as major but sub-economic concentrations (Al and Fe), eventually sufficiently locally concentrate and accumulate to produce a metallic deposit. The incremental process can be broken down into several stages that produce geological environments increasingly optimized to host ores or even to achieve the status of low-grade ore or protore themselves. In this progression the initial petrogenesis gradually changes into metallogenesis.

1. The initial stage (background) starts with a mean (average) metal content. This could be approximated by Clarke values of the bulk continental crust (as in this study), or by mean trace metal contents of different settings like oceanic crust, mantle, sea water, or other. Here reside the abundant “normal” rocks and other materials that store the bulk of all chemical elements

within the domain (Fig. 4-4) but are presently of no economic interest. Exceptions include, for example, Mg recovered from “normal” sea water.

2. “Normal” rock varieties, compositionally different from the “average continental crust”, with higher standard contents of some trace metals in respect to crustal Clarke. These include, for example, ultramafic rocks enriched in Cr and Ni by a factor of 23 and 36, respectively (3000 ppm Cr and 2000 ppm Ni against Clarke values of 130 ppm Cr, 55 ppm Ni); average carbonaceous shales with 205.ppm V, 30 ppm As, 20 ppm Mo, 8.5 ppm U, enriched 2.05 x, 17.6x, 18.2x, and 5x in respect to Clarke (Table 4-2, Figure 4-5). These rocks are the subject of general petrological and petrogenetic studies with emphasis on the major and selected trace elements with the purpose of understanding rock formation. Some ordinary rocks like ultrabasics, carbonaceous sediments and highly fractionated alkaline rocks may become exploitable ores in their own way in the future. In any case they provide metal source rocks to various superimposed mineralizations like lateritic Ni deposits.

3. Some rock varieties with published mean crustal contents have a spread of trace metal values some of which approach economic concentrations. So among basalts (mean trace Cu ~70 ppm) alkali basalt has near-Clarke trace Cu (~30-40 ppm), whereas tholeiites range between 100 and 600 ppm Cu and, as argued below, are sometimes directly or indirectly associated with major Cu accumulations as in Noril’sk (Lightfoot and Keays, 2005). The “rock” iron formation as defined by James (1966) has 15% Fe; this is not an ore, but the Minas Gerais “itabirite”, with 40% Fe, will soon be mined. Mesabi Range in Minnesota has produced 2.3 Bt Fe, contained in secondary enriched ores with 55-61% Fe, between 1890 and 1970 (Morey, 1999), out of total calculated Fe endowment of 17.28 Bt Fe in a variety of materials (Marsden, 1968). The unenriched Fe ore presently bulk mined (“taconite”) has mere 22% Fe at Hibbing, that corresponds to only 129% of Fe content of the “rock” iron formation. Bulk mining (at 100,000 t ore per day in Hibbing, in the 1990s) is economic as long as the Fe mineral is magnetite. The same reasoning applies to nepheline syenite, phonolite, anorthosite, some claystones and shales, some varieties of which have up to 20 % Al, a content approaching low-grade bauxites that are presently mined. The reason why whole massifs of high-Al anorthosite or nepheline syenite are not economic, thus of “giant Al accumulation” rank, is the high cost of Al recovery from silicate ores.

4. Rocks that are extremely enriched in some major or trace metals to approach economic grade may evolve into giant deposits. They are the extreme product of otherwise “normal”, expected evolution of the rock-forming system. At the Huangjiavan Mine, a Mo-“giant” near Zunyi, Guizhou (Mao et al., 2002), a single 20 cm thick ore bed contains 240 Kt Mo @ 5.5% and

150 Kt Ni @ 3.5%, within a 100 m thick Cambrian metalliferous black shale unit with extremely high trace, but not yet ore grade, contents of Mo, As, Ni, Se, V, U, PGE and Au. The metal ratios are comparable with those in sea water from some euxinic basins and represent an almost constant enrichment factor of 10^6 to 10^8. At Talvivaara in Finland (Loukola-Ruskeeniemi et al., 1991) an interval of Paleoproterozoic sulfidic schist in meta-ophiolites contains 0.26% and 0.53% Zn, and is now economic to mine. At Ghurayyah in the Arabian Shield (Drysdall et al., 1984; Fig. 4.6.) an isolated stock of peralkaline granite contains 3.784 Mt Zr, 993 Kt Nb, 583 Kt Y, 176 Kt Th, 93 Kt Ta and 51 Kt U in 440 Mt of ore, in the form of finely disseminated metallic minerals. Apart from the obvious problem of separation of the ore minerals to produce concentrates of the various metals, exploitation would result in a marketing problem: what to do with the difficult to market metals like Y and Th?

5. In this stage an "ore-forming" subsystem separates from, or is superimposed on, a "normal" rock-forming system. Here metallogeny (ore petrology) takes over from rock petrology, with different philosophy and methodology. This often results in research discontinuity and sectarianism among the professionals that was especially strong in the past. Merensky Reef, UG2 Reef, and Platreef of the Bushveld complex, that contain the world's greatest PGE accumulation, are clearly a part of the local magmatic evolution, but do not appear to result from an ordinatry fractionation extreme. They seem to have required a poorly understood "Factor X" to form (Cawthorn et al., 2002). The unprecedented accumulation of gold in Witwatersrand conglomerates, the sedimentogenesis of which is reasonably well understood (Frimmel et al., 2005), also owns its supergiant status to a "Factor Y" that is extensively debated in the literature; there is a spectrum of genetic opinions about the gold source ranging from synsedimentary placer to epigenetic hydrothermal influx. Large et al. (2013) offered a compromise interpretation, where a 2950-2750 Ma old gold-rich detrital pyrite was reworked into the Carbon Leader Reef from the underlying West Rand Group, then remobilized by basinal fluids during the 2100-2020 Ma events. Lightfoot and Keays (2005) described a Ni-Cu-PGE ore-forming subsystem in Noril'sk that originated in shallow basaltic magma chamber. There, a melt enriched in immiscible sulfides of Fe, Cu and Ni with PGE produced by depletion of the Nadezhdinsky stage basalt, was injected into metasedimentary roof to precipitate sulfides in crustally contaminated gabbroid sills and at skarn contacts. Most magmatic-hydrothermal fluids that formed porphyry-Cu and other deposits are products of late-stage separation of an ore-forming sub-system from a rock-forming system, gradually enriched in corresponding trace metals akin to the Stage 4 above.

6. Regressive processes/systems. Whereas stages 1-5 could be considered progressive (prograde) in respect to metal accumulation, there is a large group of deposits with many "giants" that resulted from retrograde modifications of trace metals enriched rocks (stages 2 to 4,

rarely 1) or completed ores. The "normal" and dominant regressive mechanisms like weathering, erosion and denudation tend to destroy, remove or impoverish earlier progressive metal accumulations, although occasional "spoils" can still be economic and sometimes of giant magnitude (e.g. the pallacos, debris flows composed of high-Ag fragments derived from mineralized lithocap on top of the Cerro Rico Ag-Sn system, Bolivia; Bartos 2002, 11,900 t Ag; La Quinua, 430 t Au in moraine derived from Yanacocha high-sulfidation Au outcrops above; 4.99 Mt of "exotic" Cu in Mina Sur, leached from the Chuquicamata porphyry Cu upslope, then reprecipitated below; Nelson et al., 2007). In contrast, regressive systems that selectively removed "gangue" minerals leaving enriched metal components behind, or near, resulted in a number of "giants" among Ni-laterites, bauxites, enriched Fe and Mn oxides, and others.

4.5. System magnifiers resulting in giant metal accumulations

Proposals of how ore deposits form have been made since the times of Agricola (1556) and they are becoming increasingly more sophisticated and analytically supported. The modern understanding of ore genesis is extensively and continuously publicized in the journal literature and in occasional "state of the art" works like the 2005 Economic Geology 100th Anniversary volume and the 2012 "Sillitoe Volume" about copper deposits, to which the reader is referred. The magnifiers (optimizers, enhancers) of metal accumulation are quantitative (longer-greater-stronger) and qualitative (influenced by special conditions or setting different from those that govern formation of lesser deposits). As usually, there is a transition between both. The magnifiers can be either general, or associated with a specific stage of an ore-forming system, most such systems being specific to a geological setting (geodynamic and environmental). Sample cases of exceptional metal accumulations within the existing ore forming models are reviewed below.

4.5.1. Geotectonic (geodynamic) configuration

-Porphyry deposits, especially Cu-(Mo,Au). The global distribution of the "porphyries" shows a remarkably consistent spatial association with interpreted past subduction systems, especially with the maximum occurrence of Cu deposits in magmatic belts situated about 100 km above the interpreted zones of melting along the Benioff zone. These belts project at the paleosurface 100-300 km from the former trench site depending on the angle of dip of the slab (Yakubchuk et al., 2012). The hydrous fluids or magmas released by dehydration of the subducting slab are interpreted as having ascended directly to the near-surface area possibly bringing with them metals (Cu,Au) extracted from the subducted oceanic materials, or alternatively metasomatizing and adding such metals to the mantle wedge to produce hydrous magmas that subsequently reached the shallow crustal levels where the actual mineralization took place (Candela and

Piccoli, 2005; Richards, 2003, 2011; Wysoczanski et al., 2012). Alternatively, some authors prefer a direct influx of metalliferous fluid, in association with adakites (Schutte et al, 2010; Oyarzún et al., 2001); the adakite role in metallogenesis and as a “fertility indicator” in porphyry-Cu systems was questioned by Richards and Kerrich (2007). Asthenospheric wedges thus figure prominently in the contemporary porphyry-Cu models and their positioning in respect to the presumed ascending hydrothermal fronts has been invoked as influencing giant Cu deposition. Formation of the world’s richest Central Chile porphyry-Cu segment (360 Mt Cu endowment within a 400 km interval of Miocene-Pliocene subductive margin) is attributed to slab shallowing caused by underthrusting of the Juan Fernandez oceanic spreading ridge (Skewes and Stern, 1995; Klemm et al., 2007; Perelló et al., 2012). Contributing magnifiers to Cu (Mo) super-accumulation in this setting included the presence of thick basalt-andesite “lid” (screen) that prevented volatile escape and paragenetically late, evolved, hydrous, hornblende-rich magmas that produced large, long-lasting batholith chambers with subvolcanic cupolas, high in the crust (Richards et al., 2012). Additional contributors to “giant” metallogenesis were dense fracture systems and optimal present exposure level. Elsewhere in the older (late Eocene) Chilean porphyry-Cu belt in the Precordillera, structural corridors transversal to the prevalent N-S arc trend, with magnetic signatures, facilitated formation of Cu giants like Escondida and Chuquicamata (Kloppenburg et al., 2010). The concept of oceanic ridge subduction, flattening dip of the subducting slab, subduction of or collision with oceanic plateaus (Hollings et al., 2011) and asthenosphere elevation resulting in Cu (Au, Mo) “fertile magma”, now appears extensively in the literature (e.g. in Waters et al. 2011 for the Philippine Baguio District) and has been summarized by Cooke et al. (2005). The monopoly of the deep slab melts and/or asthenosphere as the sole source of the ore metals in porphyry deposits is weakened by the empirical observation that, with the maturity and thickening of continental crust the dominant ore metals and associated intrusions change as one moves inboard into the continental interior. So Cu-Au dominated “porphyries” frequent the immature island arcs; farther inboard the Au-poor Cu-Mo systems of the Chile-style arcs predominate, to give way to metal-zoned porphyry systems with a high proportion of Zn and Pb, some of giant size (e.g. Bingham, Butte, Morococha, Antamina clusters), in settings with a thick continental crust suggesting continental sources for at least a portion of the ore metals.

Similar observation applies to Mo-containing porphyry deposits attributed to subduction. Porphyry Cu>Mo, as in the Chilean Cu mega-belt change inboard, with increasing thickness of continental crust, into Mo>Cu, to Mo, associated with metaluminous granodiorite-quartz monzonite (Endako), to eventually Climax-type high-silica rhyolite variety, both with abundant ore giants (Climax, Henderson). This is often attributed to “flat subduction” as are the high-temperature hydrothermal Pb-Zn giants in the Central Mexico and Central Peru mineral belts (Santa Eulalia, Cerro de Pasco) where the slab may have overridden the asthenospheric wedge. In the Qinling-Dabie orogen of east-central China, with the world's greatest Mo endowment in Mo-only porphyry and skarn deposits (~8.5 Mt Mo so far), Pirajno (2013) attributed this metallization to an exceptional, rapid crust thickening produced by multiple underthrusting of continental crustal slivers. Melting and Mo extraction then took place at base of this pile.

Less often invoked changes of geodynamic configurations believed to have contributed to local metal superaccumulations include:

--Bends in polar wander paths, like one at ~1640 Ma in northern Australia, believed to have contributed to the formation of the McArthur River-HYC Pb, Zn, Ag giant whereas similar bends super-charged the Mount Isa-Hilton Pb-Zn-Ag zone (Huston, 2009);

--Craton-margin setting of magmatic Ni-Cu-PGE deposits. Begg et al. (2010) argued that major mafic-ultramafic magmatic complexes positioned within less than 25 km from craton edge produced ore giants like Noril'sk-Talnakh, Jinchuan, Voisey's Bay, Thompson and others. Also, the Duluth complex included in the list, is actually near the edge of an intracratonic rift. Sudbury, now convincingly interpreted as the product of astrobleme impact, should be independent of pre-impact geotectonics. The rationale here is that zones of weakness in cratons facilitated magma ascent from mantle to produce large magma pools to store substantial amounts of trace Ni, Cu and PGE to later accumulate in orebodies. The resulting deposits, however, are a mixture of sizes so the presence of (super)giants is statistical. Sudbury is a special case. Its substantial Cu, Ni and PGE endowment (19.8 Mt Ni, 17 Mt Cu, 1180 t PGE) is presently interpreted as having separated from impact melt of quartz dioritic composition (Lightfoot et al., 2001) sourced from local (crustal) materials at 1.86 Ga (Prevec and Cawthorn, 2002; Ames et al., 2008; Dare et al., 2010); if so, Sudbury should be independent of mantle input.

--Formation and accretion of oceanic plateaus. Oceanic plateaus like the Jurassic Ontong Java still in the original location (Kerr, 2004), accrete (or are partially subducted) during collision and become one of the terranes. Composed of high trace-Cu basalt (75 to 2030 ppm Cu as reported by Kerr, 2004) they become metal source rocks during subsequent ore forming episodes. Cu, Au (Ag) giants in the 227 Ma Wrangellia Terrane in NW Cordillera (Windy Craggy, Kennecott, Greens Creek) and partly the Pebble porphyry Cu-Au may have so formed. Similar mechanism was recently suggested for a number of orogenic Au giants in structures hosted by some mafic-ultramafic greenstone terranes (e.g. the Tisdale Group with its 1,800 t Au cluster around Timmins in the Abitibi Subprovince, the Canadian Shield) as well as in the southern Barberton Au cluster (Desrochers et al., 1993). Orth et al. (1993) reported the near coincidence of the massive episode of Mesozoic sedimentation of marine black shale in the world ocean with faunal extinctions and emplacement of several major oceanic plateaus. Subsequent plume volcanism may have enriched the shale in basaltophile trace metals (Mn, Co, Ni, Cr, V, Ti, PGE) although the greatest, potentially economic enrichment in U (estimated endowment is of the order of 2.5-6 Mt U in Moroccan phosphorites alone), co-precipitated during upwelling phosphogenesis with U likely derived from continental runoff and entrapped in the reduced deposits on the sea floor (Arthur et al. 1994).

Intraplate magmatic events, initiated and controlling or controlled by mantle plumes,“hot spots”(Pirajno, 2000, 2004; Davies, 1998), also resulted in “Large igneous provinces” (Ernst and Bell, 2010; Sheth, 2007). They are associated with distinct mineralization styles like magmatogene Cr-Ni-PGE and Cu and Fe-Ti-V related to mafic-ultramafic complexes, and Nb, REE associated with alkaline systems and carbonatites. The presence of giant deposits is statistical and appear mostly influenced by quantitative indicators (bigger, longer, richer) that culminated in an extreme case of ore metals accumulations in the Bushveld Complex (Cawthorn, ed., 1996).

4.5.2. *Exceptional metal sources*

Several “secondary” deposits presently forming (and recently formed) at and near surface display direct links to their “primary” metal sources. Placer deposits of Au, Sn and Fe-Ti-Zr heavy minerals, lateritic and some duricrust deposits, gossans and secondary sulfide zones are best known. Several ore giants formed in this way owe their exceptional magnitude to anomalously trace metal enriched parent rocks (New Caledonia Ni laterites-saprolites), extensive or very rich “primary” source upslope (e.g. La Quinua Au giant in moraine deposits under Yanacocha; silver pallacas at foot of Cerro Rico, Potosi) or upstream (e.g. Sierra Nevada foothills gold placers derived from the Mother Lode System). Curiously, the 300 t Au plus Klondike placer in the Yukon lacks a prominent identified primary source and so does its much greater possible equivalent in the seven huge Witwatersrand goldfields. In addition to the major primary metals source the “secondary” giants owe their origin to efficient material transport, sorting and entrapment; suitable climate; adequate deposition sites. Long periods of steady-state formation supported large metal accumulations but an efficient post-depositional conservation was needed to prevent erosion and ore loss.

Metal sources to significant deposits where the metals accumulated in subsurface, out of sight so lacking a direct visual evidence, have been suggested ever since the days of Agricola (“metals in veins were leached from wallrocks”), but still remain controversial or are “evolving”. Metals enriched, especially high-carbon pelites, are the most frequently demonstrated metal source to tens of giant deposits.The pelites (“shales”) obtain their metal load in the syndepositional to diagenetic phases of development by direct extraction from sea water, by settling of detritus, or by contribution from hot springs or exhalations. Some metal-enriched “shales” have already achieved an economic deposit status (Talvivaara, Finland, of Ni, Co, Zn), others are kept in limbo because of environmental restrictions (the Alum Shale of southern Sweden). Most such “shales”, however, remain source rocks that required superimposed upgrading to evolve into presently economic ores. The upgrading mechanisms to form source-proximal economic deposits included tectono-hydrothermal and metamorphogenic remobilization, transfer of metals into thin but rich layers during the latest diagenesis, supergene enrichment, assimilation into magmas, and others. The first mechanism is the most frequently invoked one and has been applied to orogenic gold deposits in “shale” or “slate” sequences that host the giant deposits: Bendigo, Victoria (Thomas et al., 2011; Fig. 4-7), Sukhoi Log, Siberia; Obuasi, Ghana; Carlin, Nevada (Large et al., 2009, 2011), and others. As, Sb, Hg, Zn and other metals enriched in the “shales” co-precipitated with gold. The presumed Au and As source to the Carlin gold deposits, in the Devonian Popovich Formation, had a mean trace content of 28 ppb Au (11.2 x the Au Clarke) and 36 ppm As (21.2 x Clarke; Large et al., 2012). Willman et al. (2010) and Wilson et al. (2013), however, invoked a deeper source of trace gold to precipitate in the Bendigo lodes, in the previously unmetamorphosed (thus undepleted in gold) suite of Cambrian mafic volcanics in depth, the devolatilization of which coincided with the 440 Ma Bendigo hydrothermal system. Giant As in veins and shear zones like Obuasi or Paracatu (Brazil), with or without gold, also reside in “black shales”, the likely source of metals, and so does a number of Sb (Hillgrove, NSW; southern Bolivia; Woxi, Hunan) and Hg (Idrija, Slovenija) deposits.

Many presumed metal sources in trace metals enriched rocks are “distal”, that is not in direct contact with or in proximity to economic orebodies, hence their interpretation is more speculative. About most instructive is the case of basalt (and diabase, gabbro) as potential sources of Cu in a number of giant deposits. There are several copper giants in or at contact with mafic rocks produced by a combined magmatic separation from contaminated melt and hydrothermal transfer into skarn (Noril’sk-Talnakh; 46.73 Mt Cu), where some associated low-Ti Permian basalts contain up to 589 ppm Cu (Wooden et al., 1993). Native copper deposits sourced from trace Cu in basalt (with up to 300 ppm Cu) by metamorphic dehydration in depth, followed by fluid transfer and reprecipitation at higher crustal levels (typically within the prehnite-pumpellyite interval), in permeable basalt flowtops or in porous interflow sediments, were mined in the Keweenaw Peninsula district, Michigan (6 Mt Cu; Brown, 2006). Mount Isa copper orebodies in Queensland (8.25 Mt Cu; Perkins, 1997) are in fault contact with altered and Cu-depleted metabasalt of the Eastern Creek Volcanics, suggesting syntectonic Cu transfer. For many other copper giants the basalt Cu source is less certain. These include basalt flows and sills in red bed clastic sequences that contain “Cu-sandstone” or “Cu-shale=Kupferschiefer”-style deposits at redox interfaces (Lubin and Mansfeld “Kupferschiefer” clusters in Poland and Germany; Borg et al., 2012); Dzhezkazgan, Kazakhstan, Yakubchuk et al., 2012), as well as mafic sills and flows plus aeromagnetic anomalies possibly indicative of buried mafic intrusions under the Central African Copperbelt (Hitzman et al., 2012). At least partial Cu source relationship from proximal mafic rocks, rather than from the very distant asthenosphere, is also supported by empirical observation at Globe-Miami, Ray, Resolution porphyry copper “giants” in Arizona where widespread diabase dikes show evidence of leaching (Force, 1998). At Oyu Tolgoi, the major SW Oyu deposit is mainly hosted by altered basalt (Crane and Kavalieris, 2012) whereas at Olympic Dam the altered mafic and picritic dikes contain 425-300 ppm trace Cu (Ehrig et al., 2012). Gravity and magnetic anomalies there are suggestive of a major mafic body in depth (in addition to the obvious source of anomalies in the large Fe oxides accumulation: hematite at top, magnetite in depth).

It has been repeatedly demonstrated that rocks in the great W-Sb-(Sn, Bi, Mo) province of East-Central China (especially in the Nanling Ridge), with more then 50% share of the world endowment of these metals, are also anomalous in the same trace metals suggesting a repeatedly tapped regional metal anomaly (Li Yidou, 1993) or, alternatively, geochemical “pollution” from highly fractionated Mesozoic (“Yanshanian”) peraluminous granites (they contain 10-12 times W, Sn, Pb, Ag enrichment in respect to average Chinese granites). The largest (super)giant, Shizhouyuan in the Dongpo cluster, Hunan, is credited with 600 Kt W, 490 Kt Sn, 300 Kt Bi, 200 Kt Be, 130 Kt Mo and 76 Mt of fluorite in a complex greisen-skarn-vein system around Mesozoic biotite granite (Lu et al., 2003). The Bi and Be endowments, at least, appear overestimated.

4.5.3. Fluids that precipitate ore giants

There are two end member fluid systems responsible for exceptional metal accumulations: a) low-metal content fluids with high through-flow and long duration; b) high-metal fluids. The case a) has been confirmed by Appold et al. (2004) for the Mississippi Valley-type Pb>Zn deposits in the Viburnum Trend of Missouri (54 Mt Pb). There, the fluid compositions were “within the range of sedimentary basinal brines” and the presumably higher-grade brines have not been identified, although fluids with up to 25,000 ppm Pb, 7,100 ppm Zn, 9,100 ppm Cu may have entered episodically (Appold and Wenz, 2011). In the nearby Tri State giant Zn>>Pb district, Stoffell et al. (2008) identified brines containing thousands of ppm Pb and up to 4,000 ppm Zn that resulted from sea water evaporation. The MVT-type mineralization is interpreted as a product of fluid mixing.

Some exceptionally metal rich non-hydrothermal brine reservoirs constitute presently economic deposits in their own way (e.g. of Li), others will likely be exploited in the future. Among the unheated brines, those in the subsurface of playas in the Atacama desert are of giant magnitude (Salar de Uyuni, Bolivia, 8.9 Mt Li @ 80-1150 ppm; Salar de Atacama, Chile, 4.6 Mt Li @ 2,550 ppm). The Li was leached from rhyolite pyroclastics that underwent diagenetic devitrification. In the Kings Valley deposit in the peralkaline McDermitt Caldera, Nevada (Rytuba and Glanzman, 1985; 2.256 Mt Li), lithium released from rhyolite glass accumulated in hectorite-Li smectite. The Tibetian hot springs province, China, rivals (or even exceeds) the Andean Li deposits but information available in English is limited. Zheng (1992) has reviewed some hot spring systems there. Brines accumulated in lakes in southern Tibetian Plateau recorded average metal contents, in the Yangbajain geothermal field, of 167 ppm Li, 264 ppm Rb, 1035 ppm Cs (maximum values of 452, 470 and 3113 ppm, respectively). He recorded an annual Cs increment of 6.3 t Cs, a potentially significant component of annual Cs world production.

Two better-known geothermal systems have high content of base and precious metals dissolved in brine or precipitated in sediment at the bottom of a brine pool, they approach a giant metals accumulation. The Salton Sea, California (McKibben et al., 1988), is a subsurface geothermal brine reservoir in land projection of the Gulf of California spreading system, the second is the Atlantis II submarine hot brine pool in the Red Sea Rift (Degens and Ross, eds., 1969). The former is credited with up to 10,885 t of dissolved Ag, at ~0.1 ppm Ag, a true “giant”, with additional 6 Mt Zn and ~1.2 Mt Pb. The latter is credited with a near-giant accumulations of Zn (at 2.2%) and Ag (at 170 ppm) in bottom metalliferous mud (Hannington et al., 2005). Both examples illustrate two recent, potentially economically significant metal accumulations where the high metal contents in the ore fluids were the principal factor. Elsewhere, significant metalliferous fluid fluxes failed to produce preservable metal accumulation mostly because of the lack of entrapment mechanism, confinement, and suitable deposit sites. Simons and Brown (2007) recorded anomalous dissolved metal contents of 7.8-23 ppb Au, 1100-2400 ppb Ag, as well as high As, Sn and Hg values in hot (320^o C), deep (950-1600 m) hydrothermal fluids at Rotokawa in the Taupo zone of New Zealand. With fluid upflow of 150 kg/second, 37-109 kg Au and 5.2-11.4 t Ag/y are being lost annually. Given a 100% efficient local entrapment mechanism, a giant Au-Ag deposit (of 250 t Au, 7000 t Ag) could have been produced in as little as 2,294 years, an “instant” in terms of geological time. No economic Quaternary Au deposit has been, so far, discovered in the active Taupo geothermal system (although some may exist in depth; Krupp and Seward, 1987) and only one Au giant (Waihi) is known from the earlier (Miocene-Pliocene) epithermal Hauraki Goldfield in New Zealand, formed under similar conditions and now eroded to a depth in which most epithermal deposits formed. This illustrates the great inefficiency of natural ore forming systems where most of the metal is wasted, regardless of the high metal content in fluids. Fumaroles that are the (near)surface manifestations of magma degassing are other notorious metal wasters. White Island off New Zealand wastes 4.5 kg/y of gold, and 2.2 t/y Cu, having cumulatively delivered, but lost, ~10 Mt Cu and 45 t Au in 10,000 years (Hedenquist et al., 1993). Mount Etna in Italy, a great emitter of sulfur, is credited with wasting some 700 kg/y of gold as well as substantial quantities of Pb, Hg, Cd and Ag (Oppenheimer, 2004). So here the system, very efficient in terms of sourcing the metals, energy application, metal release and transfer failed to prevent metals dispersion and loss. At

Lardelello, Tuscany, a long-term producer of boric acid from geothermal fluid, this missing natural entrapment mechanism has been substituted by human-made installation.

In deeper-seated epizonal-plutonic systems that produce porphyry deposits, dissipation of metals carried by fluids was better prevented by the presence of roof/screen that confined the high-pressure hydrothermal system at least until it vented. Literature data on ore metal content of melt, fluid or vapour inclusions in hydrothermal systems are limited and most are of the order of 10^{2-3} ppb, but there are exceptions. Rusk et al. (2008) reported low-salinity fluids in Butte with up to 1.0% Cu. At the Alumbrera porphyry deposit, low salinity fluid contained 2% Cu and 0.1% Zn, with corresponding values at El Teniente of 1% Cu and 0.2% Zn, and at Grasberg 0.3% Cu and 0.2% Zn (Audétat et al., 2008). Lerchbaumer and Audétat (2013) credited average fluids derived from porphyry-Cu associated intrusions with 3500-6200 ppm Cu and, strangely, ~3000 ppm Cu and ~40 ppm Mo in quartz from Questa, a copper-poor Mo "giant". Schwartz and Askury (1989) recorded average trace Sn content of 27 ppm Sn in the Bujang Melaka pluton associated with the Kinta Valley giant tin accumulation in Malaya. Tin in metasomatically muscovitized granite increased up to 554 ppm Sn, reaching the values of 3080 and 7140 ppm Sn in greisen: a major source of the alluvial and regolith tin. Unusually high trace metal contents have also been reported from vapours and melt inclusions at giant porphyry-Cu deposits (Bingham; Core et al., 2006)

4.5.4. Duration of, and multiple events in mineral systems

It would seem that the longer the metal accumulating system operates, the greater will be the metal tonnage. Although sometimes true, there is no regularity. Long, uninterrupted period of slow, quiet absorption of Mo, Ni and PGE from sea water in the Zunyi district of China produced a unit of Lower Cambrian black shale enriched in trace metals but far from being of present economic interest. Within this broader envelope formed a thin layer of ore-grade material with a giant Mo accumulation (Huangjiawan deposit; 240 Kt Mo @ 5.5% Mo) as well as ore-grade Ni, and significant enrichment in As, Se, U, PGM and Au. As the metal ratios in the orebody are identical to those in the shale, Mao et al. (2002) concluded that the greater metal accumulation was proportional to a longer period of deposition, perhaps assisted by a metal-enriched ("high grade") sea water.

Among endogenous hydrothermal systems, the literature differentiates between short-lived systems lasting between about 100,000 (even ~50,000 and less-read above) and 300,000 years, and long-lived systems lasting several million years and usually comprised of a number of shorter hydrothermal pulses (Baumgartner et al., 2009). The "short" systems produced the ore giants Potrerillos-Cu, Round Mountain-Au and FSE-Lepanto; the "long" system gave birth to La Escondida, Chuquicamata, Collahuasi and Alumbrera porphyry Cu-Mo-(Au) systems as well as to the Colquijirca Zn-Pb-Ag and Cu-As cluster. It appears that duration of process is not directly proportional to the magnitude of metal accumulation. Cerro de Pasco ores formed by two pulses between 15.4 and 14.4 Ma (Baumgartner et al., 2009); Round Mountain-Au was accumulated in 50 Ky., Cerro Rico in 200 Ky., Hosen I vein at Hishikari in 260 Ky. (Velador et al., 2012). Yanacocha cluster that comprises 20 deposits (2,170 t Au) took 3 My. to form (11.5-8.5 Ma; Teal and Benavides, 2010); to this should be added the separate Quaternary retrogressive event that has produced the giant Quinua gold-bearing moraine. Longo et al. (2010) timed the Yanacocha mineralization period at 10.6 My. in 5 stages, of which the 1.2 My. long Stage 5 alone was responsible for a 777 t Au share of the whole. Sillitoe and Mortensen (2010), in their study of Andean porphyry Cu-Mo longevity, timed the duration of mineralization between 2.0 M.y. and 5.2 My; The supergiant El Teniente took 2.8 My. to form, whereas the much lesser Antapaccay formed in the course of 5.2 My. The authors demonstrated that in ore systems related to multiple intrusions over protracted time hydrothermal alteration and mineralization formed during amagmatic breaks between porphyry intrusions. The Chuquicamata Cu zone took up to 10 My. to form and at least two major events were separated by inactive periods. Remobilization of the earlier ores during late phases took place but the affected metals were retained (Ossandón et al., 2001). It is generally agreed that multiple stages of metal introduction as in Pebble, Alaska contributed to large ore tonnage and high grades (Lang and Gregory, 2012), but at the world's largest porphyry cluster of Rio Blanco-Los Bronces, and the second largest El Teniente, the last explosive stage vented and depressurized the system, terminating the ore formation and removing a portion of the previously formed ore (Toro et al., 2012; Sillitoe and Perelló, 2005).

4.5.5. Geological time and secular variation in the intensity of mineralization and preservation

"For most mineral deposit types, there are particular times in Earth history when world class to giant deposits formed and were preserved at a global scale" (Groves et al., 2005). This is due to secular evolutionary change of geological environments and conditions and, even more, to preservation of earlier formed deposits. Histogram of formation ages of all giant deposits shows a peak in the 60 to 25 Ma interval (Early-Middle Tertiary) followed by 25-2 Ma interval (Laznicka, 1999, 2006), whereas interval of similar duration during the Archean has none or few deposits of a limited range of types. Secular change has affected most deposits formed on and within a shallow depth interval of the continental lithosphere (Patchett and Samson, 2004), subjected to repeated recycling and gradual addition of the "continental" metals (lithophile metals like Sn, Li and some chalcophile metals like Pb). Mantle-related deposits (Cr, Ni, PGE) and those formed within juvenile additions to the crust by the process of subduction and accretion, changed but little; for example, about the world's oldest hydrothermal "giant" is Spinifex Ridge Mo>Cu "porphyry" in the Pilbara Craton, Australia (495 Kt Mo in 3,315 Ma host association; Jones, 1990). About the most striking effect of evolutionary change is displayed by sedimentary and volcanic-sedimentary iron deposits where the 2.7-2.4 Ga interval produced most of the "Algomatype” deposits (in the traditional terminology of James, 1983), 2.2-1.8 Ga coincided with the model banded iron formation (BIF) of “Superior-type”, and the 0.7-0.6 Ga interval was responsible for the “Rapitan-type” (Bekker et al., 2010). During the Phanerozoic the preferred style of sedimentary iron became the “oolitic” ironstone, although the “cherty iron formation” continued on reduced scale as the “Lahn-Dill type” (Schneiderhōhn, 1955). Other “time-bound” ore types of the 1960s-1970s like the Witwatersrand Au conglomerates appear more like a one-time rare geological anomaly than a reflection of prevalent contemporary environment. Similar conglomerates, although much less productive, appear in Paleoproterozoic (Tarkwa, Jacobina), Carboniferous and Tertiary. “Deep Lead” gold channel gravels in the Victoria goldfields, preserved under basalt cover (as in Ballarat), are a close equivalent at least of the Ventersdorp Contact Reef (Taylor, 1998; Frimmel et al., 2005).

Mineralization ages started to appear in the literature with increasing frequency after 1950, and they provided some assistance in large-scale exploration targeting. They, however, also retarded exploration when partial, especially regional, information was applied universally. The 1960s-1970s myth that porphyry-Cu deposits were only Mesozoic and younger, widespread throughout North America and based on the Arizona deposits, discouraged some organizations from searching for older “porphyries”, although giant Carboniferous deposits in Central Asia were discovered in the 1930s and mined since the 1940s. A crop of Paleozoic porphyry discoveries (Cadia, Oyu Tolgoi) followed later when the above dogma faded away or was ignored. A more recent concept quoted in the literature (e.g. Goldfarb et al., 2010; Maynard, 2010) and popular at conferences, is the “Boring Billion” allegory. Introduced by Holland (2005) it publicizes and provides explanation for the apparent secular gap in earth history between about 1.7 and 0.7 Ga during which relatively few (mostly sedimentogenic) deposits formed. Taken literally and universally, it would discourage the search for equivalents of Broken Hill, NSW (1,685 Ma), Mount Isa & McArthur River Pb-Zn (1,655 Ma), Olympic Dam (~1590 Ma), Aggeneys (~1,200 Ma), older generation of African Copperbelt deposits (~800-700 Ma; Hitzman et al., 2010) and other ore giants.

It appears, and is increasingly confirmed in the literature, that the present inventory of giant (and other) deposits at, and within the “economic” depth down to ~2000-3000 m under the surface, is more the consequence of post-depositional preservation than geological conditions in the time of formation (Kesler and Wilkinson, 2006). Deposits that formed under conditions of prevalent subsidence (in “geosynclines” like BIF, VMS) were preserved under thick volcano-sedimentary piles and only much later brought to the present surface and exposed by erosion (except the ocean floor mineralizations most of which disappeared down subduction zones). Deposits formed in steadily rising and rapidly eroding terrains as in magmatic arcs, like porphyry copper and epithermal deposits, and in (near)surface deposits like placers, laterites and playas, were soon removed by erosion. This has a bearing on the probabilistic estimates of undiscovered deposits remaining in various depth levels, further discussed below.

On local scale, deposit preservation was assisted by a variety of agents. So the Oyu Tolgoi deposits survived because of thrust deformation and tectonic burial to at least 1.2 km depth, shortly after formation (Khashgerel et al., 2009); the Resolution porphyry-Cu in Arizona still remains deeply buried in a graben (Hehnke et al., 2012). The Witwatersrand “reefs”, although partially eroded and cannibalized by the Ventersdorp Contact Reef, were downfaulted and buried under the thick pile of Klipriviersberg basalts, Transvaal dolomites and Karoo clastics (Frimmel, 2008). The most productive goldfields (West Wits and Welkom) still remain so buried. The Paleozoic Cu, Mo, Au ore giants of Central Asia like Almalyk and Kounrad, were preserved under younger sedimentary and volcanic rocks shortly after their formation (Yakubchuk et al., 2012), whereas in the Chilean Andes and in Arizona, young volcanism saved from erosion even the rich secondary ore blankets over porphyry copper deposits (e.g. at La Escondida).

4.5.6. Miscellaneous events contributing to giant metallogenesis

There is a mixed bag of settings and conditions that facilitated exceptional local accumulations of metals and, if their former presence could be identified in the present geology, they could be considered in target generations. Selected examples:

--Depth of emplacement of intrusions (Proffett, 2010). The upper “epizonal” plutonic to subvolcanic level (~1.5-3 km under paleosurface) is most favourable, but we now know that “porphyry” systems formed down to a depth of 8-9 km (Reed et al., 2013);

--Volume of magma reservoirs responsible for hydrothermal mineralization: large reservoirs are preferred (e.g. Dietrich et al., 2000, for the Llallagua Sn giant, Bolivia; Lightfoot and Keays, 2000, for Noril’sk);

--Special parent rock or associated sub-varieties, especially the highly fractionated ones: “adakites” for porphyry Cu (Oyarzún et al., 2001); lamprophyres for intrusion-related Au (Rock, ed., 1991); carbonatite for Nb, REE (universally applied);

--Presence of internal or external components that induced local ore precipitation from fluxing metalliferous solutions or melts like sulfur to precipitate Ni sulfides in komatiitic systems, either derived from basal pyritic (meta)sediments or from VMS systems (Fiorentini et al., 2012);

--Host metamorphic gradients: Keweenaw-type native Cu and some chalcocite deposits in flood (meta)basalts favour the prehnite-pumpellyite isograd (Jolly, 1974); most “orogenic” Au deposits in Precambrian terrains favour greenschist metamorphosed hosts (Goldfarb et al., 2005);

--Presence of evaporites as a source of sulfur (e.g. Wilde et al, 2001, for Muruntau-Au; Naldrett et al., 1996 for Noril’sk-Ni,Cu), or as impermeable screens (Hitzman et al. 2012 for the African Copperbelt);

--Other indicators including hydrothermal alterations, contact effects, structures (faults), gossans, lithocaps and others present with deposits of any size and not indicative of the super-magnitude deposits specifically. Kelley et al. (2006) collected a large number of characteristics of ore presence, some of which can be identified during field work, although they are not limited to the presence of “ore giants”.

Interim conclusions. Both quantitative and qualitative magnifiers of local metal super-accumulation have been proposed. The quantitative conditions: longer, stronger, more effective process, seem to work with any mineralization style whereas the qualitative indicators tend to be more closely associated with specific ore types.

.

5. Discovery of ore giants: history

5.1. The changing discovery methodology

Search for, and discovery of an ore deposit, of any size, are influenced by two principal sets of consideration: 1. Geology: is it likely to contain the desired deposit, or any deposit? 2. Politics, economics and technology: Do the present local regulations allow, or even encourage, exploration? If a deposit is found and proven economic, will permits be issued to mine it and what would be the tax regime? If so, will mining be economically and technologically feasible and profitable? Is the project location safe, well served by infrastructure? What is the knowledge base, data availability, government-produced information such as maps and reports? The Fraser Institute in Vancouver, British Columbia, produces annual surveys and ranks a number of world jurisdictions by their attractiveness to investment in the field of mineral exploration and mining (www.fraserinstitute.org); the surveys are based on responses from hundreds of mining executives, are considered reliable, widely used and free to download (in 2012-13 the best jurisdiction out of the ranked selection was Finland, the worst Indonesia!).The items evaluated are described on the institute’s website. The Fraser Institute surveys assist in a selection of where to go, explore and then mine. Favourable geology is essential as it is permanent, while restrictive politics may change. Geological understanding has gradually increased, almost exponentially, in the past century, and is becoming ever more complex with time. A chronological survey of discovery of ore giants follows (Tables 5-1, 5-2; Figures 5.1, 5.2).

Now, what “discovery” actually means? When Patrick Hannan with two partners discovered the gold-mineralized outcrop of what is now the Golden Mile deposit in Kalgoorlie, Western Australia, it was possible to put an exact date on this event (1894; Fig. 5-3). Mining started shortly afterwards as proving, drilling, resource calculation was not practiced then and government bureaucracy was minimal. Instant visual ore discoveries in outcrop are rare these days, but they do happen (e.g. discovery of Voisey's Bay-Ni in Labrador in 1994 by two geologists who made an unplanned helicopter landing on a gossanous outcrop). Most recent and near-past deposit finds have resulted from a prolonged chain of projects, events and tasks, mostly performed by teams, where the moment of "discovery" is hard to determine and such moments are rarely specified in reports. Yanacocha discovery history started before 1859, intensified after 1970, with bulk Ag potential identified in 1984, followed by gold potential in 1986. Gold production started in 1993 and Au resources kept increasing on a yearly basis (Teal and Benavides, 2010). So the "discovery" dates listed below should be considered approximate; the most recent discovery dates usually apply to drill intersection of the orebody, although new discoveries only enter quantitative databases once reserves/resources have been calculated and announced.

5.2. Ore giants found before the year 1492: From the Chalcolithic period to re-discovery of the Americas

The earliest ore giants discovery, although their exceptional magnitude had not been recognized then, took place as early as 4000 to 3000 B.C. in the Middle East, in the Mediterranean, in China; there is not enough information about the very early discoveries by the native populations in Africa and Latin America. It is believed that first metal finds in a region had been unplanned, made by accident by lay persons but once found and mined, further search in the proximity of the deposit and elsewhere was pursued by (semi)professional miners/prospectors. The earliest 3000 B.C. era ore discoveries we now recognize as giant deposits include Rio Tinto and Tharsis Au-(Cu) in Spain (active around 3015-2530 B.C.; Leblanc et al., 2000), Au deposits in the Eastern Desert of Egypt (probably around the now resurrected gold deposit Sukhari near Mersa Alam near the Red Sea coast) and possibly some Cu deposits in the Kerman belt, Iran, with the presently operating giant Sarchesmeh. Bor and Majdanpek-Cu in Serbia also claim a Bronze Age heritage.The oldest major Cu-(Au) discovery in China quoted by Pirajno (2013) was the Fenghuangshan deposit in the collectively giant Middle-Lower Yangtze district. The ~1,200-1 B.C. period contributed several silver (and Pb; Zn was not utilized then) giants (Lavrio in Greece; Skarpelis and Argyraki, 2009, Konofagou, 1980; Cartagena and Linares-La Carolina in Spain, Iglesiente district in Sardinia) found and exploited by the Phoenicians and Greeks, as well as Dabaoshan, Dexing-Cu (Pirajno, 2013) and Gejiu-Ag (afterwards Sn, Cu; Gejiu Museum) in China. Many ancient workings for gold and copper in the Arabian Shield like Mahd adh Dhahab were first mined around 1000 B.C., then in the early Islamic period 1250-750 years ago (Lowther, 1994; Fig. 1.1 above). The Roman period gave us Roşia Montană-Au in Romania (where A.D. 100 workings are still preserved in the local mining museum; Fig. 1.1) as well as

Cornwall-Sn and probably Almadén-Hg in Spain. There have been few recorded discoveries of ore giants in the Old World in the long period between A.D. 1 and 1492 although Medieval mining intermittently continued in the Erzgebirge (Altenberg-Sn), Harz Mts. and foreland (Rammelsberg-Pb,Ag, discovered in 968 and Mansfeld-Cu, discovered in 1150). Additional European discoveries include Upper Silesia Pb-Zn, ~1200; Idrija-Hg, 1490, in Slovenia and Trepča-Pb,Zn ~1,300 in Kosovo. Kolar and Hutti-Au in India operated around A.D. 1 and so did several major mines in China (Jiaodong-Au, ~100 A.D). The famous, in their times "world class" silver deposits Jáchymov, Kutná Hora and Banska Štiavnica did not reach the present giant magnitude threshold, with the possible exception of Sala (Sweden) and Freiberg (Germany); Fig. 5.4.

5.3. From 1492 (re-discovery of the Americas) to ~1750 (onset of the Industrial Revolution)

The (re)discovery of the Americas by European seafarers, followed by conquest and plunder of the native societies, resulted in identification and rapid exploitation of a number of deposits of giant magnitude. These included gold in Colombia (giant Marmato, possibly the fabled El Dorado, and lesser deposits in Antioquia) and silver in Mexico, Peru, Chile and Bolivia. Presumably, these deposits (Pachuca, 1522; Potosí, 1545; Fresnillo, 1546; Andacollo, 1568) had been discovered and mined by the locals before the arrival of the conquistadors and it is surprising that such technologically advanced native pyramid builders in Mexico, Guatemala and Bolivia still used stone tools and utilized metals (Au, Ag) only for ornaments and statues so the deposits of Cu, Sn and Pb were not discovered until much later. The next generation of Latin American discoveries were mainly the result of professional but still visual discoveries by prospectors and miners (San Cristóbal, Bolivia, 1630; Titiribí-Au, Colombia, 1793) and they included copper (Chuquicamata, 1600s; El Teniente, 1706).

The huge influx of cheap silver to Europe from the Americas triggered an early financial crisis and devastated domestic silver mining. Small scale native copper mining in Katanga was active in the 1500s but accurate record is missing; modern large scale mining had to wait until the colonial period. The same applies to gold mining in Ghana (formerly Gold Coast) and tin mining in Malaya and western Indonesia.

5.4. From 1750 to 1900: colonialism, Industrial Revolution, and opening of the American West

Of the number of scientific contributions made in this time period the discovery of previously unknown chemical elements has had the greatest impact on the materials industry. By the year 1900, ninety of the naturally occurring elements had been known and most practically utilized.

This, together with technology (steam, electricity, transport) accelerated mining and with it exploration and deposit discovery, assisted by establishment of state geological surveys (first in Britain, in 1848). The surveys made substantial contribution to geology and ore finding in the form of maps and publications, and their staffs assisted in a number of mineral discoveries. There were relatively few finds of new giant metallic deposits in Europe (Meggen-Zn, 1852), but discoveries proliferated in overseas colonies and in the great northern Asian landmass in extension of the Russian Empire. In colonial Africa, the Central African Copperbelt-Cu; Tarkwa and Obuasi-Au, 1880 and 1885; Tsumeb-Pb, 1892; Central Rand-Au, 1886; were found. Australia contributed Bendigo-Au, 1851; Broken Hill-Pb, Zn, Ag, 1883; Kalgoorlie-Au, 1894, where important new mine discoveries started mere six years after finding the first Australian metal mine, the insignificant Glen Osmond-Pb, Ag on the outskirts of Adelaide. Russian Siberia, Central Asia and the Far East yielded the giants Nezhdaninskoe-Au, 1749; Dzhezkazgan-Cu, 1760; Ridder-Sokolnoe-Pb,Zn, 1784; Lena gold placers,1884.

The most dramatic discovery boom, however, took place in North America: a colony, later (USA) an independent republic. Initially considered good for timber and pelts only (especially in Canada), with the native population using virtually no metals, the change came with the westward rush. There, the gold placers in the Sierra Nevada foothills were discovered in 1840 and their bedrock source, Mother Lode/Veta Madre, few years later. Comstock Lode Au-Ag, 1859; Leadville-Ag, Pb, 1874 and Tri-State-Zn, Pb, 1848, followed. A large number of oxidized Cu occurrences were found in the American West and mined on a small scale (Bingham, 1863; Santa Rita, 1801; Butte, 1874) but it took several decades before many of these occurrences were recognized as giant porphyry copper deposits and bulk mined from open pits in the next century (read below). Climax, the giant Mo deposit in the Rocky Mountains, was first staked in 1879 as a graphite prospect and it took 16 years to reinterpret it as a Mo deposit. In Canada, the first metallic deposit found (Bruce Mines-Cu) was a midget. The huge Sudbury “basin” was noted twice (in 1856 and 1883), but developed only in the 1900s (Fig. 5.5). In Canada, the West had to wait: Sullivan-Pb and Highland Valley-Cu were both found in 1892 and the 19th Century there terminated with the 1896 Klondike gold rush. Long et al. (2000) demonstrated that the greatest number of “significant deposits” of Cu, Pb, Zn, Ag and Au in the United States were discovered between 1866 and 1892 (283 deposits, 11 per year), whereas the post-World War 2 (1946-1996) added 264 finds (4-7 per year).

Most of the period discoveries were made by prospectors/miners, travelling on foot, on burros and in canoes. Most prospects were worked immediately after discovery in a basic way, without much resource proving. The ore finds were visual, sulfides indicated by gossans, or for gold by panning towards the source (Boyle, 1987). Few deposits were discovered by government officials, in colonies assisted by information provided by the local population. Others were found by geological survey officers in course of their duties, often in arduous conditions.

The physically impaired George Dawson of the Geological Survey of Canada walked, in the late 1800s, for 5000 km across the wilderness when an early winter interfered with his more orderly return to Ontario from the Yukon. Availability of maps was limited and the prospecting was not efficiently targeted for the lack of geological awareness. When a discovery had been made the vicinity was prospected in search for analogues. Primitive drilling had barely started and early geophysics were represented mostly by magnetic compass upheavals. Yet despite the rather chaotic process, most visually distinct deposits of the “classical” metals in outcrop have been found, leaving the future generations with the hard to detect remnants and concealed mineralizations.

5.5. A century of accelerated ore discovery and exploitation:1900 to 2013

It would be tempting to start this century in 1913, on strength of publication of the book Traité de Métalogenie by Louis de Launay that initiated metallogeny and increasingly more integrated scientific approach to regional mineral interpretation. But several important years would have been lost.

The “golden age” of ore giants has really started after the year 1900, although a number of important discoveries had been made several years earlier (e.g. of the Witwatersrand in 1886, Kalgoorlie in 1894; Table 5-1; Figure 5.2). The 20th Century started with an almost complete inventory of 90 naturally occurring metallic and other elements discovered by then (except for hafnium and rhenium discovered in the 1920s), some of which already had practical utilization that drove demand. The new bulk-mining technology from open pits, initially applied to porphyry copper deposits in the American West (at Bingham Canyon in 1906), greatly reduced the average and cut-off grades needed for profitable mining. Bulk mining and megapits required property consolidation and substantial capitalization met by the prolific growth of corporations as well as banks and financial houses. New processing technologies, especially flotation and later solvent extraction, made it possible to lower the grade and exploit complex ores of intimately intergrown fine minerals, so practical utilization of the primary VMS and sedex deposits (although not so called then) started. Learning and application of mineral deposits geology has moved from descriptions of individual deposits (although valuable) to consideration of their geological setting and mutual relationships, Excellent and factual descriptions of American deposits in the U.S. Geological Survey Professional Papers and, since 1905, in the journal Economic Geology, migrated into textbooks and classrooms, bringing the leadership in Economic Geology to the New World from Freiberg. Economic advances due to capitalism (and, after 1917, Soviet revolutionary socialism under which, despite the bureaucracy and political oppression, a large number of major deposits were discovered) created a growing need for minerals, a need accelerated by two destructive World Wars. Sadly, many of the resource breakthroughs like development of synthetic nitrates around 1916, new aluminium smelting technology, Mg from sea water and nuclear technology in the 1940s, were driven by the war needs. Early 20th Century globalization, applied within the colonial context then followed by free markets, accelerated the world-wide ore search with increasing rate of discovery. The discovery of giant deposits peaked in the 1980s (Fig.5.2) and the ratio of concealed to outcropping deposits has steadily grown. Case histories of major mineral discoveries are popular with industry professionals. Short accounts are scattered in literature describing geology of ore deposits, more can be found in several volumes dedicated to this genre (e.g. Hutchinson and Grauch, eds., 1991; Hollister, ed.,1990; three volumes). Unfortunately, little is available in English about the impressive discoveries during the Soviet and Socialist China periods except for the Gulag literature (Gulags opened up and exploited the Soviet Far Eastern gold province).

Visual outcrop discoveries of ore giants, some assisted by simple techniques like panning and float tracing, continued until about the 1960s with important finds made in hard to reach areas lacking settlements and communications (e.g. in Canada: Cobalt-Ag in 1903; Timmins gold camp found in 1909; Kirkland Lake-Au in 1911; Windy Craggy in 1958. In Australia, Mount Isa-Pb, Zn was found by prospectors in 1923, McArthur River-HYC in 1955). A memorable sighting of malachite-coated magnetite outcrop 150 km from the coast by Jacques Dozy in 1936 led to gradual discovery of the Ertsberg-Grasberg Cu-Au cluster in Indonesian Papua (Mealey, 1996).

The era of non-instrumental visual prospecting was in fast decline. Some outcropping deposits like Howards Pass-Zn,Pb (Fig. 5.6) were missed when a geological party walked over the rocky outcrop in alpine tundra, without noticing anything unusual because of the extremely fine-grained nature of the ore and a lack of gossan. The deposit was finally recognized in 1972 to trigger a Zn exploration rush in northern Canadian Cordillera but although the Howard's Pass zone was greatly extended, no separate similar deposit has been found in the area. After about 1950 prospectors started to use portable equipment like Geiger counters that assisted in discovery of the early generation of radioactive deposits like Elliot Lake-U in Ontario in 1953 and Grants district in New Mexico in 1950, small diameter ("X-ray") drills, magnetometers and torsion balances. The Felbertal scheelite deposit in the Austrian Alps, the second largest tungsten resource in Europe, was a rare case of a full-scale discovery by academics in the 1960s. It was inspired by the Munich University stratiform model (Höll and Maucher, 1976). Dr. Rudolf Höll made the actual discovery by traversing the Hohe Tauern Alps at night, with an ultraviolet lamp. The important Carajás iron province was first sighted from the air in 1967, indicated by infertile clearing in the Amazon rainforest (Machamer et al., 1991). Bush pilot's sighting of rusty creeks in the 1960s eventually resulted in the discovery of Red Dog in Alaska (Koehler and Tikkanen, 1991).

From the 1960s on most mineral search has been conducted by companies and corporations, using an increasingly more sophisticated mix of exploration technologies and relying on a growing public availability of background information like geological, geochemical and geophysical maps, reports, literature, government drill core libraries, empirical and conceptual models, results of earlier exploration projects, and others. A typical “greenfield” ore search project started with an area selection based on geological favourability indicated by published information and personal expertise when available, and politico-economic feasibility, followed by an office-generated model. The subsequent field component typically included some airborne geophysics followed by ground geophysics and geochemistry, and lots of drilling. A number of overlapping techniques have been applied and a number of persons involved, so it has become difficult to attribute discovery to a particular technology or to a person. Creative personalities guiding the search and not afraid to depart from a group-think of the day, however, deserve much credit for exploration success.Teamed with academics and government geologists, industry geologists developed a number of widely used mostly empirical mineralization models applied to porphyry copper alteration zoning (Lowell and Guilbert, 1970); unconformity uranium (Cameron, ed., 1983; compare Fig. 4.3.); “sandstone” uranium (Finch, 1967); VMS (Sangster, 1972); iron-oxide copper, gold, IOCG (Hitzman et al., 1992). All these models were based on significant type deposits and resulted in a chain of giant ore discoveries. The rate of discovery has greatly increased after the year 1950 (Figure 5-2). Table 5-1 (it includes only giant and some “world class” deposits with reported discovery dates, not all known “giants”) records 6 deposits found in 1950; 4 in 1952; 12 in 1955, 6 in 1962; 10 in 1967; 9 in 1968, 6 in 1986, 8 in 1991, 8 in 1994, 6 in 1988, 38 between 2000 and 2013. About 20-30 potential “giants” are under way to enter the database in 5 to10 years time when impressive drill intersections reported in the literature like the SEG Newsletters, reach the stage of resource calculation and announcement. Since the year 1950, 307 significant discoveries included in Table 5-1 and Figure 5-2 have been absolutely dominated by copper (129 deposits, 42%) followed by gold (77 deposits, 25%). Some periods like 2000 to 2007 include only Cu and Au and there is a clear discovery trend towards virtual Cu and Au monopoly after the 1970s. This is clearly due to economic factors (demand and price) rather than geological availability. In case of gold it reflects the phenomenal price increase from the official $ 33/oz in 1970 to the peak approaching $ 1,900/oz in 2011 (these prices are not corrected for cost of living increases) and also to the diminishing trust in U.S. dollar as the world’s reserve currency. In addition to this, the relatively simple and cheap leaching technology has made it possible to rapidly start and terminate production and repatriate much of profits within the often narrow “window of stability”, especially in countries with high investment risk. The copper discovery popularity is due to the steadily increasing utilization (in electrical applications) and also to reduced cost of the leaching-electrowinning technology that makes it economic to process ores with as little as 0.2% Cu. A number of the copper giants listed are not yet in production so they do not contribute to oversupply. Mudd et al. (2013) identified the global resource of 1.81 Bt Cu divided among 730 projects. From geological point of view, Cu deposits are easier to predict and find than deposits of other metals, as most are porphyry-copper in relatively predictable settings. The trend since about the 1960s has been to maximize porphyry-Cu discoveries in established belts (mostly Chile, southern Peru, less in the American West), on their fringe (northern Peru to Ecuador, Argentina, northern Mexico), and then to identify and explore new "porphyry" terrains.

New or rejuvenated porphyry-Cu provinces with prolific "giants" were identified in Alaska and British Columbia, in Panama, in Serbia, Romania and Bulgaria; in Kazakhstan and Uzbekistan; in Lesser Caucasus through to Iran and Baluchistan; from the Himalayas to Yunnan and Burma; in Jiangxi, Mongolia, Chukotka; in NSW; in New Guinea (island) and Melanesian Arc. Scattered Precambrian paleo-porphyries and meta-porphyries (Aitik, Malanjkhand, Spinifex Ridge) extended the selection of potential Cu targets much farther as did the IOCG style popularized after the Olympic Dam discovery in 1975 (Haynes, 2006). The outstanding porphyry-dominated Cu-supergiant clusters discovered after 1950 include La Escondida cluster (122.7 Mt Cu, discovered in 1987), Ertsberg-Grasberg (72.6 Mt Cu/1967), Oyu Tolgoi (39 Mt Cu/1996), Pebble in Alaska (40 Mt Cu/1989), perhaps Peschanka in Chukotka, Russia (27 Mt Cu?), plus new deposits and extensions added to the established clusters and zones of Rio Blanco, Chuquicamata and El Teniente. The sole IOCG Cu supergiant, so far, is Olympic Dam (78.52 Mt Cu). Post-1950 gold (near) supergiants include the Carlin Trend, especially the Goldstrike deposit (1,800 t Au, 1985; Fig. 5.7a), Muruntau (5290 t Au, 1958; Fig. 5.7b), Yanacocha (2177 t Au,1983) as well as the expanded resources in existing gold deposits (Kalgoorlie, Obuasi) and gold component in the Cu super-giants Pebble (3,337 t Au), Ertsberg-Grasberg (6,380 t Au; Fig. 5.7c) and Olympic Dam (3,179 t Au). Although "most deposits in known porphyry Cu districts have been discovered" (Richards, 2003), Sillitoe (2010) noted that in the Pacific arcs "availability of Cu and base metal deposits exposed at surface is not decreasing".

Compared with Cu + Au discovery of ore giants, other metals have made a lesser impact although they include a number of supergiant metal accumulations. New Zn finds (19 "giants" discovered) include Red Dog (31 Mt Zn/1969), McArthur River-HYC (20.88 Mt Zn / 1955), Howards Pass (38.5 Mt Zn/1972; Fig. 5.6) as well as the expanded earlier discoveries (Mount Isa belt). Pb "giants" (12 discoveries) include the super-giant Viburnum Trend (39.7 Mt Pb/1955) as well as Pb component in most Zn deposits. Mo (17 discoveries) include newly found buried "giants" in the Rocky Mountains (Henderson, 1.243 Mt Mo) and especially the newly emerging East Qinling Mo province in China (~8.5 Mt Mo endowment). The greatest Mo tonnages are, however, stored in several porphyry Cu-Mo deposits like the Chuquicamata zone (8.51 Mt Mo).

Nickel has few post-1950 "geochemical giants" (about 8) because of its relatively high clarke, but major new discoveries include Jinchuan (5.4 Mt Ni), Voisey's Bay (2.85 Mt Ni), Thompson belt (6.01 Mt Ni).The greatest sulfidic Ni endowment is in enlarged resources of the pre-1950 systems like Noril'sk-Talnakh (28 Mt Ni), Sudbury (19.8 Mt Ni), and in New Caledonia laterites. Uranium (12 post-1950 finds) has been discovered in 8 major new provinces (Athabasca, Alligator Rivers, Chu-Sarysu, Agadez Basin, Central Aldan, Krasnokamensk, Namibia, Gawler Craton) with 10 "giants", not considering the by-product U in phosphorites. The single largest U tonnage is in the Complex Cu, U, Au, Ag, REE deposit Olympic Dam (1.992 Mt U, Ehrig et al., 2012), a true #1 discovery of the 20th Century worth about $ 1.4 Trillion in contained metals. The remaining metals accounted for substantially lesser exploration activity and resulting discoveries, although these include several significant (super)giants. The outstanding one is Shizhouyuan skarn/greisen in Hunan, the world's largest repository of Bi (300 Kt), Be (200 Kt); Lu et al. (2003), as well as W, Sn, Mo, Pb and Zn; that is, provided the endowment figures are reliable. In addition to Felbertal in Austria (260 Kt W), most new giant W and Sn discoveries have been made in China (Pirajno, 2013). At least five significant Li-brine playas in Atacama and Nevada have been identified and some brought into production, not counting the insufficiently publicized Li, Rb, Cs hot springs on the Tibetian Plateau. No new rare earths giant deposit has been reported, at least none even marginally competitive with Bayan Obo. Niobium got one new supergiant (Seis Lagos in Amazonia, 57 Mt Nb). Platinum metals (5 significant discoveries) now have additional giants in the Stillwater Complex of Montana (JM Reef, 10,961 t PGE), in the Duluth Complex of Minnesota (2,261 t PGE) and in several Precambrian mafic intrusions in Finland, although the greatest endowment still remains in the pre-1950 discoveries in Bushveld and in the Great Dyke.

In terms of host countries, the post-1950 discoveries of giant and some significant deposits in Table 5-2 are dominated by the very large countries (USA-45 discoveries; Australia, 33; Canada, 32; Russia, 19 and China 18, although Russia and China are probably underrepresented because of insufficient information) (Table 5.2). Chile (38 discoveries) and Peru (19), both middle-size countries, are much better endowed in ore giants in relation to their area. This is the consequence of high proportion of porphyry-Cu, the dominant giant type discovered worldwide, as well as exploration-supporting government policies, at least in the past 30 years. South Africa has the greatest variety of giant deposit styles and metals (Fig. 5.9). On the reverse side of giants' discovery stands the giants' demission (Fig. 5.10) through exhaustion, although some past casualties have been subsequently revived.

6. How have giant deposits been found?

6.1. Discovery techniques

Despite the ever growing exploration complexity and costs (Fig, 6-1), some disciplines and/or methods are credited with a greater share of exploration success than the rest.

6.1.1. Stream and soil geochemistry followed by drilling

This is the #1 exploration technique that has made greater than average contribution to discovery of many ore giants. As a practical application of the "academic" geochemistry advanced by A.E. Fersman (1933) and V.I. Vinogradov, it was applied on a mass scale in the USSR since the 1930s. Whole new mineral provinces were discovered by teams based in dozens of regional exploration "expeditions". Outside the USSR, geochemistry has been an integral component of exploration methodology since the 1950s and has made an essential contribution in discovery of at least 75% of metallic deposits in outcrop and under shallow cover- too numerous to name. Highlights include discovery of the Carlin gold deposit in Nevada by Newmont in 1961-1962, and with it recognition of the new type of "invisible" gold deposits, missed by prospectors. A number of "look-alike" discoveries followed. Also missed by prospectors, despite the existence of a small oxidized outcrop, soil geochemistry discovered the Century-Zn deposit in northern Australia, in 1990. Geochemistry, combined with mapping, traversing, examination of leached outcrops and air rotary drilling, succeeded in discovery of the La Escondida Cu super-giant in Chile (Lowell, 1991). No geophysical techniques were applied in the prospecting phase. More recently, biogeochemistry has been used in exploration for precious metals (Dunn, 1992) and other metals.

6.1.2.Tracing of glacial boulder trains to bedrock and float interpretation

Glacial erratics contributed to discovery of a number of northern deposits, although mostly of sub-giant size, like Outokumpu and Vihanti-Cu, Zn in Finland, Fäboliden-Au in Sweden, Key Lake-U in Saskatchewan. Giants so discovered include the Swedish Laisvall-Pb and Aitik-Cu, and partly the Thompson Nickel Belt in Manitoba. Following mineralized float to its hard-rock source is a standard technique used in prospecting.

6.1.3. Air and ground radiometry

The mass campaign of uranium exploration, practiced in the USSR and its satellites after World War 2 by a variety of means, was a remarkable success. Dozens of vein U deposits were found in the German and Czech Erzgebirge that was the cradle of uranium discovery and mining, but none was of giant magnitude (the largest Schlema-Alberoda had 80.6 Kt U). Two different U giants have, however, been found on the fringe. They are Ronneburg-Kauern near Gera in Germany (211 Kt U) and Hamr-Stráž in the Czech Republic (230 Kt U); compare Fig. 3.3. The former deposit has remobilized pitchblende patches along faults transecting U-rich graptolite black shale, the latter is a "sandstone-U" on base of Cretaceous basin. "Greenfields" exploration in the former USSR have established new U provinces in the Ukrainian Shield (Zholtye Vody), Aldan Shield (Elkon), Krasnokamensk on the Mongolian border (Streltsovka), Navoi-Uchkuduk basins in Uzbekistan and the Chu-Sarysu sandstone U province in Kazakhstan. The latter three are of giant magnitude. The Soviet uranium exploration was conducted by a secretive military-industrial complex that occasionally found important deposits other than uranium, that they passed to the more open sectors of the state mining industry. The Au supergiant Muruntau (Fig. 5.7) and giant Vasil'kovskoe were so discovered. In the rest of the world airborne, then ground, radiometry assisted in discovery of initially the outcropping, later buried U deposits in the Athabasca province in Canada, and in the Alligator Rivers province in Australia. There, Ranger was detected by airborne radiometry in 1969, Jabiluka in 1971. Even before, in the 1950s, the first generation of U deposits in Canada: the Beaverlodge metasomatized shears and the Elliot Lake U-conglomerates were discovered by prospectors using simple portable scintillometers. As new uranium discoveries in Saskatchewan have slowed down, Marlatt and Kyser (2011) call for "paradigmatic shift" in exploration philosophy, bringing in more knowledge.

6.1.4. Aero- and ground magnetics

Magnetic methods ranging from primitive (compass and dip needle) to sophisticated magnetometers are credited with discovery and delineation of most magnetite deposits and provinces like the Kursk Magnetic Anomaly (KMA) in Russia and in the Kiruna area of Sweden. In the Witwatersrand, the outcrop discovery of the first conglomerate "reef" at Langlaagte (Harrison Park) in 1886 was followed into increasing depth by mining (Fig. 6-2), until fault-bounded horsts were encountered that terminated the "reefs". In the 1930s a weak magnetism, produced by the Magnetic Shale marker near top of the almost unmineralized West Rand Group, was followed under deepening cover westward and it indicated the possible presence of the mineralized Central Rand stratigraphically above; this was later confirmed by drilling (Krahmann, 1936). This resulted in discovery of the deeply buried Au "reefs" in the most productive Rand goldfield, the West Wits. Drilling coexisting magnetic and gravity anomalies in the Gawler Craton of South Australia resulted in discovery of the super-giant Olympic Dam in 1975 (Ehrig et al., 2012) followed by giants Prominent Hill in 2003 and Carrapateena in 2006. An aeromagnetic anomaly followed by drilling in 1982-1983 resulted in discovery of the Abra polymetallic deposit in Western Australia, under 200-500 m of clastic rocks (Boddington, 1990), as well as the Cannington Pb-Ag deposit in Queensland (1990).

6.1.5. Electrical and electromagnetic methods

The earliest successful application of electrogeophysics is attributed to Thomas Alva Edison, whose experiments at the fringe of the Sudbury Complex contributed to discovery of the Falconbridge Ni deposit. After the year 1950 induced polarization (IP), resistivity and other methods assumed dominant role in the discovery and proving of sulfidic deposits (VMS, porphyry, veins and replacements). Main success story includes discovery of the Kidd Creek VMS deposit in Ontario indicated by airborne electromagnetic anomaly, followed by ground EM and drilling. At Yanacocha, resistivity has been applied to identification of gold-bearing silicified ledges whereas at Hishikari this method is used to identify buried gold-quartz veins. At Oyu Tolgoi, gradient array IP combined with resistivity contributed to discovery of a number of deeply buried porphyry Cu-Au deposits along a 25 km long trend; the Heruga deposit was found by IP in 2005, under 500 to 1000 m of volcanic and metasedimentary cover (Crane and Kavalieris, 2012). The new Zeus IP technology introduced in 2009 extended the depth of ore detection five times compared with the conventional instrumentation, detecting anomalies as deep as 3,500 m.

6.1.6. Gravimetry

Large scale maps of Bouguer anomalies and derivatives are now available for most world jurisdictions and they are used in preliminary prospectivity assessments. They can delimit and extend established mineralized terrains like the Colorado Mineral Belt, marked by negative Bouguer anomaly attributed to granite emplaced into reactivated shear zone (Lerchbaumer and Audétat, 2013). In Witwatersrand, the Eötvōs torsion balance was used in the 1930s-1940s to define the thinnest Ventersdorp basalt cover to position drilling sites for intersecting the deeply buried Central Rand Group, especially the Ventersdorp Contact Reef on base of the basalt (Minter et al., 1986). Detailed application of airborne and ground gravimetry contributed to discovery of Olympic Dam and other IOCG deposits in the Gawler Craton (read above). Drilling of gravimetric anomalies resulted in discovery of the Masa Valverde VMS in Spain in 1986, although at Neves Corvo, in the same Iberian Pyrite Belt, the first drill hole based on a large positive Bouguer anomaly was barren. Hole #2, positioned on a combined gravity and electric anomaly, intersected massive sulfides in 350 m depth (DeCarvalho, 1991). Subsequently, four more ore lenses have been found.

6.1.7. Other techniques

Seismic methods have had limited application in ore search, being applied to identify sub-sea sand bodies with heavy minerals; basement surfaces under unconsolidated cover; fault traces. In Witwatersrand seismic methods helped to identify upper and lower contacts of the Central Rand Group and to detect upthrown blocks. At the South Deep Mine seismic reflection was applied to contour the Ventersdorp Contact Reef. In Victoria Goldfields hammer seismics were used to delineate gravel channels under basalt flows. Colour airphotos indicated Quebrada Blanca and Cerro Casale; radar images assisted in discovery of Seis Lagos-Nb; non-invasive spectroscopy like PIMA supplemented ore search in the barren Atacama desert.

6.2. Ore giants discovered by re-examining old mineral occurrences and workings

A single overwhelming contributor to exploration success has been the presence of known mineral occurrences in an area, economic or not. At least 70% of discoveries between 1960 and 1999 had been made in the “brownfield” environment (“within the shade of a headframe”), especially in case of buried deposits. Ore giants have been found by drilling in mines nearing exhaustion, in abandoned mines, uneconomic prospects or old diggings, around reported metallic showings, or in terrain adjacent to and within mine clusters. The Arabian Shield is littered by hundreds of old gold and some copper workings going back 5000 years and largely forgotten (compare Fig.1.1). Recently compiled inventories have facilitated exploration, bypassing the field prospecting stage and several mines now operate (Mahd-adh Dhahab, Sukhaybarat); none of them of giant magnitude, so far. Old Roman gold workings in Asturia, Spain, long forgotten and unrecognized, led to mining renewal in Salave and Rio Narcea clusters. More recent abandoned mines led to the discovery of giant Au+Cu Cadia cluster in New South Wales (Wood, 2012), of the San Gregorio Zn-Pb “giant” in the Colquijirca cluster in Peru under old oxidic bismuth mine; of the giant Resolution porphyry deposit under Magma Mine in Arizona. The soon to become giant Hillside Cu-Au-Fe deposit in the Gawler Craton of South Australia was indicated by a hundred years old digging, but has only been discovered by Rex Minerals in 2008, by drilling a combined magnetic and gravity anomaly. Inventories, databases and maps of mineral occurrences, now maintained by most geological surveys, are of great practical help. “Greenfield” discoveries in areas without or with limited mining history are substantially more costly and risky so they are much less frequent, but some have resulted in spectacular new discoveries and they established new mineral provinces. They are applied to remote areas with difficult access, areas previously inaccessible for political reasons, overburden covered areas. Search for new ore types in established mining areas are intermediate between the greenfield and brownfield settings. Exploration for concealed deposits is a special, growing discipline discussed in more detail below.

6.3. Deposits under cover

Few major deposits not exposed on surface had been found before the year 1900, unless they resulted from underground operations originally initiated at the surface (example: discovery of the Neues Lager orebody in 1859 that elevated Rammelsberg into the giant category; Sperling 1973). The change came with the increasing application of geophysics and drilling. Of the approximately 600 entries listed in Table 5-1 (this table does not include all “giants”), and types of cover shown in Fig.6.3, about 69 entries (11.5%) have been discovered under shallow, mostly unconsolidated cover, and about 60 entries (10%) under deeper, hard-rock cover. Of the former deposits about 6 (not listed in Table 5-1) have been found under lakes and playas, about 3 under the sea but of continental provenance, and about 3 under glacier ice, at least partly (Kumtor-Au, Kyrgyzstan). About 18 “giants” were covered by alluvium and desert duricrusts (Kalahari-Mn). Exotica-Cu (Mina Sur) is an oxidic Cu impregnation and infiltration in arid alluvium. Additional examples of “giants” under alluvium include Gold Quarry-Au found in 1979; Twin Creeks-Au found in 1986; Pipeline-Au found in 1991; Cortez Hills-Au found in 2002, all in Nevada (Muntean and Taufen, 2011). Similar alluvium-buried deposits include Mesquite-Au in California (Willis and Tosdal, 1992), Radomiro Tomic-Cu in the Chuquicamata zone. About 22 “giants” with few significant deposits in Canada, Siberia and Scandinavia, and at high elevations in the Andes, were covered by unconsolidated glacial sediments and one or two are mineralized glacial deposits themselves (Quinua at Yanacocha-Au). At least 25 “giants” and some significant “large” Ni deposits were found under, or coincide with, deep tropical regoliths (laterite & saprolite). The “gold laterite” type of deposits has been recognized in the 1980s and by now has over a dozen followers worldwide, although none of the giant magnitude alone. In several instances the near-surface Au laterites were revealed to be an expression of a more valuable primary mineralization underneath, as in Igarapé Bahía, Brazil and Boddington, Western Australia. Boddington (Symons et al., 1990) started as a bauxite deposit in the Darling Ranges south of Perth, where a portion of the bauxite and associated regolith were found to be gold bearing, eventually producing 140 t Au @ 1.8 g/t by the time of closure in the early 2000s (Fig. 6.4). The tropical regolith at Boddington is underlain by a vein and stockwork gold and copper mineralization in Archean greenstone belt with an endowment of 954 t Au @ 0.65 g/t and over 1 million tons of copper and, since the start of hardrock mining at the end of the 2000s, it has been the second most productive gold producer in Western Australia. Boddington discovery was not only about gold: a previously unrecognized small greenstone belt relic, surrounded by high-grade gneiss terrain, was discovered as well.

About 18 “giants” were at least partially buried by young volcanics and pyroclastics. These include solid, almost impenetrable flood basalts (Ballarat-Au,”deep leads”) and unconsolidated to semi-consolidated intermediate to felsic flows and fragmentals (e.g. Escondida-Cu). Volcanic cover, emplaced on paleosurface shortly after development of supergene enriched zones over porphyry coppers, preserved these highly erodable materials until recently (Livingston et al., 1968). The thickness of shallow covers ranges from several meters down to about 300 m.

About 60 “giants” in or under hard rocks can be broadly subdivided into those in established mineralized regions (“brownfield” terrains) and those discovered in areas with none or limited mining history (“greenfield” regions). The former include most of the buried Witwatersrand goldfields west and east of the Langlaagte 1886 discovery outcrop near present day Johannesburg, in Central Rand. In Witwatersrand the gold “reefs” have been proven down to a depth of almost 5,000 m (at Anglogold's Western Ultra Deeps Mine), and are presently mined from the depth of 3,500 m in West Rand and from around 2 km depths in the West Wits and Welkom Goldfields (compare Fig. 5.9). The gold "reefs" there were discovered by deep drilling around 1934 and 1939, respectively. Comparable depths with buried giant metal accumulations have only been reached in the Polish Basin and the Fore-Sudetic Monocline (Kaleje and Sulmierzyce-Cu, Poland; 3,000 and 1,500 m depths; Figure 6-4). Most other "brownfield" buried discoveries were made in depth of several hundred meters and include porphyry-Cu deposits drill-intersected under higher-level epithermal deposits (Butte, Montana, under high-grade Cu-As veins; Borska Reka under high-sulfidation replacement pyritic bodies at Bor, Serbia; Far South East porphyry under the Lepanto high-sulfidation Cu-Au; numerous deposits in the Oyu Tolgoi Trend; Resolution deposit under the Magma replacement-Cu body). At Cadia, NSW, Almalyk, Uzbekistan, Los Pelambres, Chile and San Manuel, Arizona, buried porphyry deposits East Cadia, Dalnee, Frontera and Kalamazoo have been found under and adjacent to outcropping orebodies. Examples of buried deposits found in mineralized areas include Goldstrike (Post-Betze) deposit in the northern Carlin Trend (Fig. 5.7), found in 1986 and now the single largest gold deposit in United States; Alemão IOCG orebody in the Igarapé Bahia deposit, Brazil; Merlin high-grade shear-related Mo orebody in the Mount Dore Cu deposit in Queensland; Récsk, Hungary, porphyry and skarn deposit; U deposits under the Athabasca sandstones, some with phenomenal grades (Cigar Lake and McArthur River; 7.9% and 13.51% U; Bruneton, 1987). In mineralized mega-belts with a long mining history like the Iberian Pyrite Belt in Iberia and the Urals, new generation of buried VMS deposits discovered between 1950 and 1980 include Neves-Corvo in Portugal (Relvas et al., 2006), Masa Valverde and Las Cruces in Spain, Uzel'ga, Pavlovskoe and Gai in the Urals. Buried deposits in areas without mining history include the Suwalki Ti-magnetite in NE Poland (Charlier et al., 2009), Admiral Bay Zn-Pb in NE Western Australia, and others.

7. Conclusions: ore giants in the future

7.1. Where are the future ore giants?

Until the end of the 19th Century the (then comparatively small) world demand for metals was met by cumulative production from a mix of mines that, although it included several deposits we now recognize as giant, mostly consisted of small to medium-size labour-intensive operations. Ore giants increased in importance after the year 1900 with the onset of bulk mining from open pits and high-capacity underground mines, to become the dominant metal source today. At present, between 60 and 95% of mine production of metals comes from ore giants and they also contain the bulk of future resources. The cumulative tonnage of 3,182 Mt of copper that resided in giant deposits, unevenly distributed among 10 types (Fig. 7.1) even exceeds the 3 billion tons Cu figure quoted by the U.S. Geological Survey. What is the share of the lesser Cu deposits that are not included?

The tonnage figures on which this study is based ideally represent the quantities of metals present in a deposit before the mining has started ("geological resources") and they do not indicate the remaining resources as variable quantities of metals have already been produced and the resources depleted. Mudd et al. (2013) assessed the actual world Cu resources as 1,860 Mt Cu. Many famous giant deposits of yesterday are now exhausted and closed (Fig. 5.10) whereas others continue with rapidly diminishing resources because of increasing depth and deteriorating political-economic conditions (Witwatersrand). Given the recent annual global Cu mine production of around 16-17 Mt the "number of years at 2001 production" figure of 197.7 years in Table 3-1 is too optimistic as it includes metal already mined in the past, but even a reduced assured Cu supply expectation (say, 100 years) is not sufficient. The graph of ore discovery ages (Figures 5.1 and 5.2), absolutely dominated by Cu and Au finds, shows that in "good years" the new discoveries replenished the mined-out copper and some even provided a surplus, but more years resulted in deficit. To replenish 16-17 Mt Cu/year requires annual discovery of another two or three "mid-giants", a difficult task that cannot be guaranteed. Copper and gold have been most popular with explorers in the past century and the number of deposits found provides a safety margin to the politico-economic vagaries like embargoes, wars, nationalization, taxation changes, environmental restrictions and others. Adverse actions of one government are thus unlikely to cause serious global supply interruptions of these metals, but this is not the case with many other metals the resources of which are virtually monopolized by a small number of countries (Cr, PGE, V by South Africa; REE by China). Recent restriction of rare element metals exports from China resulted in global shortages, met by accelerated exploration elsewhere and search for substitutes. Despite this, a number of giant deposits of various metals, discovered and explored in the past, still remain in ground for a variety of reasons (Table 7-2)

So where the future supplies of metals will come from? The ore giants will likely retain their primacy until at least the end of this century. With their gradually diminishing long-term importance (that will outlive the virtual disappearance of lesser deposits), the "unconventional resources" will take over and the rate of recycling will greatly increase. In the meantime, however, the search for the ore giants will continue. How many are likely to be found? This varies with each metal, geological setting and jurisdiction. I believe there remain less than 20% of undiscovered outcropping Cu deposits in the world, most of them small to medium-size, left to be found; this is close to zero in exploration saturated areas with a long mining tradition. The corresponding figure for gold is about 20-30%, for the rest of metals between 10 and 50%. A large number of recorded occurrences and small former mines of most metals, however, does exist and most recent “discoveries” resulted from advanced exploration methods applied to them. Most future giant discoveries are thus likely to be concealed, under cover that ranges from several metres of unconsolidated alluvium, glacial sediments or tropical regolith to hundreds or thousands meters of solid rock overburden (Figure 6.3). Muntean and Taufen (2011) documented the exploration history in the “Carlin-type” gold province in the Great Basin, Nevada, from the initial discovery of the newly defined ore style in 1961/1962 to the present. It shows a discovery trend initiated by outcropping deposits (6 out of 24) turning into ore finds under cover; not a single exposed deposit has been discovered after 1986. The depth of overburden there ranged from several meters of alluvium to 600 m of solid rocks. The exploration methodology was dominated by geochemistry, some geophysics, followed by drilling. Wood (2012) documented the chronology of discovery of increasingly deeper Cu-Au orebodies in the Cadia (NSW) cluster that started with re-examination of two small abandoned mines from the late 1880s. De Carvalho (1991) described the evolving ideas and exploration technology that eventually resulted in discovery of the first concealed sulphide lens in the Neves Corvo cluster.

Various pronouncements by “experts”, mostly made at conferences, tend to sound reassuring, implying that increasingly deeper mining will deal with basically the same frequency of ore occurrences per area as at the present surface. The logic here is that the presently outcropping or shallow deposits are mostly the product of exhumation of previously buried deposits, hence the depth level of, say, 1000m, will still contain the equivalent of deposits now at the surface (the 1000 m depth level is still relatively undepleted by mined-out ores). The above idea, however, neglects the fact that many deposits formed at surface and in shallow depth and if not subsequently buried they will have been removed by erosion/denudation, the effectiveness of this process being proportional to the vertical extent of the various ore types (Figure 7-2). Particularly vulnerable are ore types of short geological lifespan that are born at, and die with the exposed (paleo)surface. I estimate that in the depth of 100 m under the present surface some 80% of placer deposits will be lost, representing some 3% of the global resource base of Au, 10% of Sn, 30% of Ti, Zr and REE (Table 7-3). The same depth will likely preserve less than 20% of lateritic bauxite, Ni-laterites, and supergene enriched Fe and Cu ores resulting in a global resource deficit of ~50% Ni, ~70% Al, 20-30% Fe. Playa lake brines, presently the largest Li resource, will disappear.

The depth of 1000 m under the surface will likely be depleted in epithermal deposits, depth of 3000 will miss some 60-70% of porphyry deposits. The per-area number of the VMS, orogenic Au and BIF deposits will likely not change down to some 5000 m depth and the number of deposits in high-grade metamorphic rocks and some mafic intrusions may actually slightly increase. Kesler and Wilkinson (2008, 2009) presented a quantitative reasoning about the ephemeral nature of mostly shallow metallic deposits, most of which were lost to denudation throughout the Earth history. What is left, therefore, is a mere fraction.

So where are the remaining buried ore giants going to be found? In respect to existing mineralized areas: 1) in-between two or more known deposits; 2) around (in clusters or belts) of existing deposits; 3) in extension of the mineralized units under cover. The 1) is exemplified by the discovery of La Escondida, under thin volcanic cover, about midway between El Salvador and Chuquicamata deposits along the Falla Domeyko trend (Lowell, 1991). Case 2) is the standard product of resource growth in mineralized clusters and zones that start with an initial discovery, as in the Carlin-Great Basin area and Cadia already mentioned above. More outstanding examples include the growth of the Oyu Tolgoi Trend (Crane and Kavalieris, 2012), multiple birth of new deposits in the Toki cluster and the entire Chuquicamata belt (Rivera et al., 2012), The presently very active Sulphurets epithermal and porphyry Au-Cu cluster in northern British Columbia, where the first claim was staked in 1935, has evolved into a fast growing Au super-giant comprised of three giant Au and Cu deposits totalling 2,654 t Au, 4.5 Mt Cu, and 291 Kt Mo (Snowden, 2012), and is still growing. Case 3) is represented by the continuous enlargement of the Platreef-PGE trend in the northern Bushveld prong under the younger cover (Cawthorn et al., 2005), and by advance into the NW extension of the Katanga Copperbelt that resulted in the giant Kamoa discovery (24.13 Mt Cu in 2013, considered the presently largest undeveloped high-grade Cu deposit in the world; Parker et al., 2013; www.ivanplats.com). Kamoa is a stratabound-Cu horizon found at base of the Lower Kundelungu Group, in diamictite association (Schmandt et al., 2013), in a setting not previously considered prospective.

In covered areas where mineralization is expected to be in the basement or close to the cover/basement unconformity on both sides, discoveries have been made by drilling and this will continue. Under most favourable conditions geophysical anomalies are drilled, but frequently they are extremely weak as under the Athabasca Plateau in Saskatchewan, yet successful holes resulted in discovery of the McArthur River and Cigar Lake uranium deposits (Bruneton, 1987). In several successful cases “giants” were discovered by drilling through a cover along a widely-spaced grid in a mineralized province unsupported by geophysics (Spence-Cu discovery in Chile by Rio Algom), or by W.H. Callahan’s “random walk” drilling venture during which the buried Elmwood (Central Tennessee) Zn cluster was found (Kyle, 1976). Several buried giants were accidentally discovered by drilling for other purpose like for hydrocarbons (Admiral Bay-Pb,Zn in northern Australia; deep Cu discoveries in Permian dune sandstone in the Polish Basin; Récsk porphyry-Cu in Hungary), for water, for stratigraphic information. It is possible that thorough examination of drill core (when available) and cuttings from oil fields as in the Middle East or from the rapidly growing “fracking” operations elsewhere might include signs of overlooked metallic ore presence. The technology of horizontal drilling from subsurface and hydraulic fracturing that has revolutionized hydrocarbon extraction in the past several years, has a potential of extracting soluble metallic components from deeply buried metalliferous rocks-a technology presently applied to production of a growing proportion of U from the “sandstone-U” deposits as in the Chu-Sarysu and Navoi Basins in Kazakhstan and Uzbekistan. The enormous repository of metals held in the deep seated Bazhenov Shale of Siberia (Gavshin and Zakharov, 1996) might enter the market by this mechanism.

7.2. Frontier provinces and “hot areas”

With the exception of few countries/lands closed on political (North Korea) or environmental (Antarctica) grounds, mineral exploration has been truly global at least since 1991 and its intensity fluctuated with the market demand “rushes” (“coltan”=Nb+Ta in the 1990s; Li, REE in the 2000s), and local political changes. Au and Cu have been the main targets followed by Fe and U and the “technology” metals of the day; these metals also produced the largest number of the “ore giants”. “Hot areas” of the last two decades included: the James Bay Lowland in Quebec and Ontario (Au, REE; Langevin et al., 2012); NW British Columbia (Au, Cu in the Sulphurets camp); SW Alaska (Pebble-style porphyry-Cu, Donlin Creek vein Au); southern extention of the Carlin and Getchell Trends (Au); central Mexico (Guerrero and Zacatecas) VMS and Au-Ag veins (Fitch, 1999); N-C Colombia (Au); SE Ecuador and northern Peru (porphyry Cu, Au); Atacama salars (Li); fringes of Chilean porphyry-Cu trends; Patagonia (Deseado Massif, Au); broader Carajás Cu-Au province, Brazil; ice-free Greenland (Fe, Zn, Au, Cu, REE, Ta (but government regulations do not allow uranium mining!); NE Finland (Au, Ni, PGE); Lena, Amur and Kolyma placer-Au areas, search for primary Au; southern Gobi, Mongolia (porphyry & epithermal Cu-Au, REE); East Qinling province, China (Mo, Au); fringe of the Nanling Ridge and Jiangxi tungsten province, China (W, Sn, U, Be); southern Tibet (Cu, Au); Central Asian clastic “basins” (U); Turkey (Cu, Au); western Africa (Au); fringe (Lufilian Foreland) and extension of the Central African Copperbelt (Cu, Co); Gawler and Curnamona Cratons, South Australia, especially the Woomera Prohibited Area now partly opened to exploration (Cu, U, Au); extension of the Victoria Goldfields under cover (Au); Cloncurry area, northern Queensland (Cu,Au,U); fringe of the Yilgarn Craton, Western Australia (Au, e.g. Tropicana); Albany-Fraser mobile belt, Western Australia (Ni, Cu, Au in high-grade metamorphic terrain); and others. All these areas have “ore giants” potential but the presence of super-size deposits is statistical and cannot be predicted. Geologically promising jurisdictions awaiting political improvement include Afghanistan, Iran, parts of Colombia, Venezuela. And if everything fails, we can capture and mine asteroids! (Bush, 2006).

8. Epilogue. The next 100 years of ore finding: looking for ore remnants, rejects and misfits near surface, identifying new metal source materials, and exploring in increasingly greater depths and in oceans, within legislative loopholes

The 1900 (or even 1913) world was very different from the present one. Much of it was colonized by a handful of great powers, the two world wars and socialist revolutions were yet to happen, there were no airliners and airports, no nukes, and mere 2 billion of people!. Large patches of the map of the world were blank, geological mapping had barely started, and hundreds of giant and supergiant metal deposits were yet to be found. By now they have been discovered and worked, some already to extinction, and this greatly depleted the inventory of future "easy" discoveries. In the year 1900, the Witwatersrand gold basin was mere 18 years old and it included just a small area in extension of the discovery outcrops in the Central and West Rands.The more productive buried goldfields waited fifty more years to be found. In 1900 it was still possible to mount a burro or jump into the canoe and head into the bush or desert where no serious prospector had ever been, unencumbered by learned hypotheses arguing that your target area "had no potential". Those who ventured out found Cobalt, Timmins and Kirkland Lake, and opened up the Abitibi Sub-province, by now the source of over 5,000 tons of gold with much copper and zinc. The two world wars followed by the Cold War swallowed much resources to build war toys that were rapidly blasted to pieces, many of which returned back to Mother Nature from where they originally came. But it was nothing compared with the post-1950 exponential growth trends: in population, in consumption, in technology (including weapons capable of wiping us all in the matter of hours), in pollution, environmental degradation, and resources depletion.

The boom period of ore giants' discovery between about 1960 and late 1990s is slowly fading away despite the occasional bursts of success fuelled by economic cycle, The frequency of giant discoveries will eventually reduce to a trickle and the cost of finding them will skyrocket. Alternative metal sources will increasingly augment, and eventually replace, metal supply that is today coming predominantly from the classical "ore giants". It is up to the global economics, politics and technological progress to make it possible (Schodde and Hronsky, 2006). There is no shortage of metals as such as the humanity can eventually tap the 160 trillion tons of copper and 424 trillion tons of zinc envisaged by Cathles (2010) as "lying at the base of the (oceanic) sediment layer", or the 954 Bt Zn, 241 Bt Cu in VMS deposits forming at spreading ridges (Cathles, 2011). Talented, well educated, open-minded, enthusiastic people will be needed to make this happen.

In the meantime the steadily more sophisticated exploration on land will continue, yet the time-tested exploration approach of searching for the "look alike" equivalents of significant deposits (Muessig, 2011) will be with us for a long time, both in outcrop and in drill core. For many years ahead “those who see the most rocks win” (Hitzman, 2011, paraphrasing H.H. Read), engaging in “traditional geological fieldwork (will continue) to be essence of the discovery process underpinned by willingness to drill” (Sillitoe, 2010), and “the critical factors that underpin exploration success (will still lie) in a geologist’s ability to recognize new opportunity” (Sillitoe, 2010). Let’s hope that our education system, increasingly oriented towards costly satisfaction of scientific curiosity, will recognize the practical “new opportunity” as well.

Acknowledgments

This paper has benefitted from assistance I have received from Adelaide University, AME-BC, MRAG Canada (Terence Ortslan), KIGAM Korea (Se Won Chang), Jingwen Mao, Eiji Izawa, K. Watanabe, as well as my family. Hartwig Frimmel, one anonymous referee and Franco Pirajno reviewed this paper and made valuable comments. Thank you.

References

Abbott, J.E., Van Vuuren, C.J.J, Viljoen, M.J.,1986. The Alpha-Gravelotte antimony ore body, Murchison greenstone belt, *in*: C.R Anhaeusser, S. Maske, eds, 321-332.

Agricola, G., 1556. De Re Metallica Libri XII. English translation by H.C and L.H Hoover, 1950. Dover, New York, 638 p.

Ahlfeld, F.E. and Schneider-Scherbina, A., 1964. Los Yacimientos Minerales y de Hidrocarburos de Bolivia. Bolivia Dept Nac Geol Bol 5.

Aitchinson, L., 1960. A History of Metals. Macdonald & Evans, London, 747 p.

Ames, D.E., Davidson, A., Wodicka, N., 2008. Geology of the gient Sudbury polymetallic mining camp, Ontario, Canada. Econ. Geol. 103, 1057-1078.

Andersson, A., Dahlman, B., Gee, D.G., Snäll, S., 1985. The Scandinavian alum shales. Sveriges Geol Unders, Ca 56, pp 1-50.

Appold, M.S., Numelin, T.J., Shepherd, T.J., Chenery, S.R., 2004. Limits on the metal content of fluid inclusions in gangue minerals from the Viburnum Trend, Southeast Missouri, determined by laser ablation ICF-MS. Econ. Geol. 99, 185-198.

Appold, M.S. and Wenz, Z.J., 2011. Composition of ore fluid inclusions from the Viburnum Trend, Southeast Missouri district, United States: Implications for transport and precipitation mechanisms. Econ. Geol. 106, 55-78.

Arce-Burgoa,.R. and Goldfarb, R..J., 2009. Metallogeny of Bolivia. SEG Newsletter 79, 1-15.

Arkhangel'skaya, V.V., Kazanskii, V.I., Prokhorov, K.V., et al, 1993. Geological structure, zonality, and formation conditions of the Katugin Ta-Nb-Zr deposit (Chara-Udokan region), Eastern Siberia. Geol Ore Dep, v35, 100-116.

Arthur, M.A. and Sageman, B.B., 1994. Marine black shales-depositional mechanisms and environments of ancient deposits. Annual Reviews of Earth and Planet. Sci. 22, 499-551.

Audétat, A., Pettke, T., Heinrich, C.A., Bodnar, R.J., 2008. The composition of magmatic-hydrothermal fluids in barren and mineralized intrusions. Econ. Geol. 103, 877-908.

Barcellos da Silva, 1986. Jazida de nióbio de Araxá, Minas Gerais, *in*: Schobbenhaus, C., Coelho, C.E.S, eds, v 2, 435-453.

Bárdossy, G., 1982. Karst Bauxites. Elsevier, Amsterdam, 441 p.

Bárdossy, G, and Aleva, G.J.J, 1990. Lateritic Bauxites. Elsevier, Amsterdam, 624 p.

Bartos, P.J., 2000. The pallacas of Cerro Rico de Potosi, Bolivia: A new deposit type. Econ Geol, 95, 645-654.

Baumann, L., 1976. Introduction to Ore Deposits. Scottish Acad Press, Edinburgh, 131 p.

Baumgartner, R., Fontboté, L., Spikings, R., Ovtcharova, M., Schaltegger, U., Schneider, J., Page, L., Gutjahr, M., 2009. Bracketing the ages of magmatic-hydrothermal activity at the Cerro de Pasco epithermal polymetallic deposit, Central Peru: A U-Pb and $^{40}Ar/^{39}Ar$ study. Econ. Geol. 104, 479-504.

Begg, G.C., Hronsky, J.A.M., Arndt, N.T., Griffin, W.L., O'Reilly, Y.O., Hayward, N., 2010. Lithospheric, cratonic and geodynamioc setting of Ni-Cu-PGE sulfide deposits. Econ. Geol. 105, 1057-1070.

Belevtsev, Ya.N., Belevtsev, R.Ya., Siroshtan, R.I., et al, 1983. The Krivoi Rog Basin, *in*: A.F. Trendall, R.C. Morris, eds, Iron Formation. Elsevier, Amsterdam, 211-251.

Belevtsev, Ya. N., ed., 1974. Metalogeniya Ukrainy I Moldavii. Naukova Dumka, Kiev, 510 p.

Belich, J., 2009. Replenishing the Earth. The settler revolution and the rise of Anglo-world, 1783-1939. Oxford Univ. Press, 573 p.

Bentor, Y.K., Mart, J., 1984. The metalllogenic map of Israel, *in*: Mém. Explic. de la carte Metall. de l'Europe et des pays limitrophes. UNESCO, Paris, 537-541.

Bercé, B., 1958. Geologija ležišta žive Idria. Geologija, Ljubljana, v 4, 5-62.

Bezrukov, P.L., Petelin, V.P., Skornjakova, N.S., 1970. Mineral'nye resursy okeana, *in*: V.G. Kort, ed, Tikhii Okean, v 2. Nauka, Moscow, 419 p.

Bilibin, Yu.A., 1951. Metallogenic provinces and metallogenic Epochs, English Translation. Geol Bull, Dept Geology, Queens College, NY, 35 p

Blainey, G., 1970. A theory of mineral discovery: Australia in the nineteenth century. Economic History Review, 23, 298-313.

Bloch, S., 1980. Some factors controlling the concentration of uranium in the world ocean. Geoch Cosmoch Acta, 44, 373-377.

Blundell, D.J., Kornkowski, D.H., Alderton, D.H.M., Oszcepalski, S., Kucha, H., 2003. Copper mineralization of the Polish Kupferschiefer: A proposed basement fault-fracture system of fluid flow. Econ. Geol. 98, 1487-1496.

Boddington, T.D.M., 1990. Abra lead-silver-copper-gold deposit, *in*: F.E. Hughes, ed, 659-664.

Borg, G., Piestrzynski, A., Bachmann, G.H., Puttman, W., Walther, S. and Fiedler, M., 2012. An overview of the European Kupferschiefer deposits. SEG Spec. Publ. 16, 455-486.

Box, S.E., Syusyura, B., Seltmann, R., Creaser, R.A., Dolgopolova, A., Zientek, M.L., 2012. Dzhezkazgan and associated sandstone copper deposits of the Chu-Sarysu basin, Central Kazakhstan. SEG Spec. Publ. 16, 303-328.

Boyle, R.W., 1987. Gold: History and Genesis of Deposits. Van Nostrand Reinhold, New York, 676 p.

BRGM+CIGCES, 2004. The Gondwana metal potential GIS: A Gondwana interactive CD-ROM of geology and mineral deposits of Gondwana. CD-ROM.

Brown, A.C., 2006. Genesis of native copper lodes in the Keweenaw district, northern Michigan. A hybrid evolved meteoric and metamorphogenic model. Econ. Geol. 101, 1437-1444.

Bruneton, P., 1987. Geology of the Cigar Lake uranium deposit (Saskatchewan, Canada) Saskatchewan Geol. Soc. Spec. Publ. 8, 99-112.

Burrows, D.R. and Lesher, C.M., 2012. Copper-rich magmatic Ni-Cu-PGE deposits. SEG Spec. Publ. 16, 515-551.

Busch, M.W., 2006. Feasibility of asteroid mining. SEG Newsletter 65, p.20.

Button, A. 1979. Early Proterozoic weathering profile on the 2200 m.y. old Hekpoort Basalt, Pretoria Group, South Africa: Preliminary results. Inform. Circ. Econ. Geol. Res. Unit, Univ. Witwatersrand, No 133, 20 p

Cameron, E.M., ed., 1983. Uranium exploration in Athabasca Basin, Saskatchewan, Canada. Canad. Gov. Publ. Centre, Ottawa, 310 p.

Camus, F., 1975. Geology of the El Teniente orebody with emphasis on wall-rock alteration. Econ. Geol. 70, 1341-1372.

Candela, P.A. and Piccoli, P.M., 2005. Magmatic processes in the development of porphyry-type ore systems. Econ. Geol. 100th Anniv. Vol., 25-38.

Cathles, L.K., 2010. A path forward. SEG Newsletter No.83, 18-20.

Cathles, L.M., 2011. Is the ocean a very large VMS district? Joint Ann. Meeting of the GAC-MAC-SEG-SGA, Ottawa; Powerpoint presentation.

Cawthorn, R.G., ed., 1996. Layered Intrusions. Elsevier, Amsterdam.

Cawthorn, R.G., Barnes, S.J., Ballhaus, C. and Malitch, K.N., 2005. Platinum group elements, chromium, and vanadium deposits in mafic and ultramafic rocks. Econ. Geol. 100th Anniv. Vol., 215-250.

Cawthorn, R.G., Merkle, R.K.W. and Viljoen, M.J., 2002. Platinum group element deposits in the Bushveld Complex, South Africa. Canad. Inst. Min. Met. Petrol. Spec. Vol. 54, 389-430.

Chao, E.C.T. et al., 1997. The sedimentary carbonate-hosted giant Bayan Obo REE-Fe-Nb ore deposit of Inner Mongolia, China. U.S. Geol. Surv. Bull. 2143, 65 p.

Charlier, B., Namur, O., Duchesne, J-C, Wisniewska, J., Parecki, A., Auwera, J.V., 2009. Cumulative origin and polybaric crystallization of Fe-Ti oxide ore in the Suwalki Anorthosite site, Northeastern Poland. Econ. Geol. 104, 205-222.

Chaykin, S.I., 1985. Tectonic character and structural features of the KMA ferruginous siliceous formation. Geotectonics, v 19, 16-30.

Clark, A.H., 1993. Are outsize porphyry copper deposits either anatomically or environmentally distinctive? Soc. Econ. Geol. Spec. Publ. 2, 213-183.

Clark, K.F., Dow, R.R., Knowling, R.D., 1979. Fissure-vein deposits related to continental volcanic and subvolcanic terranes in Sierra Madre Occidental province, Mexico. Nevada Bureau of Mines and Geol, Rept 33, 189-210.

Clarke, F.W. and Washington, H.S., 1924. The Composition of the Earth's Crust. U.S. Geol Survey Profess. Paper 127, 117 p.

Conofagos, C., 1980. The Lavrion and the ancient Greek techniques for silver production. Ekdotiki Athinion, Athens, 458 p.

Cooke, D.R., Hollings, P., Walshe, J.L., 2005. Giant porphyry deposiots: characteristics, distribution, and tectonic controls. Econ. Geol. 100, 801-818.

Core, D.P., Kesler, S.E. and Essene, E.J., 2006. Unusually Cu-rich magmas associated with giant porphyry copper deposits: Evidence from Bingham, Utah. Geology 34, 41-44.

Cornwall, H.R., 1951. Differentiation in lavas of the Keweenawan Series and origin of the copper deposits of Michigan. Geol. Soc. Amer. Bull. 62, 159-202.

Crane, D. and Kavalieris, I., 2012. Geologic overview of the Oyu Tolgoi porphyry Cu-Au-Mo deposits, Mongolia. SEG Spec. Publ. 16, 187-214.

Crowson, P., 1998. Minerals Handbook 1998-99. Statistics and analyses of the world's minerals industry. Mining Journal Books Ltd., London, 438 p.

Cunningham, C.G. et al., 2007. A preliminary quantitative mineral resource assessment of undiscovered porphyry copper resources in the Andes Mountains of South America. SEG Newsletter 71, 1-13.

Dahlkamp, F.J., 1993. Uranium Ore Deposits. Springer-Verlag, Berlin & Heidelberg, 460 p.

Dare, S.A., Barnes, S-J, Prichard, H.M., Fisher, P.C., 2010. The timing and formation of platinum-group minerals fronm the Creigton Ni-Cu-platinum group element sulphide deposit, Sudbury, Canada: Early crystallization of PGE-rich sulfoarsenides. Econ. Geol. 105, 1071-1096.

Davies, G.F., 1998. Plates, plumes, mantle convection, and mantle evolution, *in*: I. Jackson, ed, The Earth's Mantle. Cambridge Univ Press, 228-258.

Davis, L.J., 1991. Spor Mountain beryllium deposits, Juab County, Utah, *in*: V.F. Hollister, ed, v 3, pp 325-332.

deCarvalho, D., 1991. A case history of the Neves-Corvo massive sulfide deposit, Portugal, and implications for future discoveries. Econ Geol Monogr 8, pp 314-334.

Degens, E.T., Ross, D.A., eds., 1969. Hot Brines and Recent Heavy Metal Deposits in the Red Sea. A Geochemical and Geophysical Account. Springer-Verlag, 600 p

deSouza, M.M., 1996. The great niobium deposit in Morro do Seis Lagos, North Brazil. 30th Intern. Geol. Congr. Beijing, Abstract.

Desrochers, J.P., Hubert, C., Ludden, J.N. and Pilote, P., 1993. Accretion of Archean oceanic plateau fragments in the Abitibi greenstone belt, Canada. Geology 21, 451-454.

Dietrich, A., Lehmann, B., Wallianos, A., 2000. Bulk rock and melt inclusion geochemistry of Bolivian tin porphyry systems. Econ. Geol. 95, 313-326.

Dietz, R.S., 1972. Sudbury astrobleme, splash-emplaced sublayer and possible cosmogenic ores. Geol. Assoc. Canada, Spec. Paper 10, 29-40.

Dill, H.G., 2010. The "chessboard" classification scheme of mineral deposits: Mineralogy and geology from aluminum to zirconium. Earth Sci. Reviews 100, 1-420.

Drysdall, A.R., Jackson, N.J., Ramsay, C.R., Douch, C.J., Hackett, D., 1984. Rare element mineralization related to Precambrian alkali granites in the Arabian Shield. Econ. Geol, 79, 1366-1377.

Ehrig, K., McPhie, J. and Kamenetsky, V., 2012. Geology and mineralogical zonation of the Olympic Dam iron oxide Cu-U-Au-Ag deposit, South Australia. SEG Spec. Publ. 16, 237-268.

Eckstrand, O.R., 1996. Magmatic nickel-copper-platinum group elements, *in*: Geology of Canada, No 8. Geol. Surv. Canada, 584-605.

Emmons, W.H., 1937. Gold deposits of the World. McGraw-Hill, New York, 562 p.

Emmons, S.F., Irving, J.D., Laughlin, G.F., 1927. Geology and ore deposits of the Leadville mining district, Colorado. U.S. Geol. Surv. Prof. Paper 148, 368 p.

Ernst, R.E. and Bell, K., 2010. Large igneous provinces (LIPs) and carbonatites. Miner. Petrol. 98, 55-76.

Ewers, G.R., Evans, N. and Kilgour, B., 2002. OZMIN mineral deposits database. Geoscience Australia AGSO Record 2000/18, 103 p.

Farmer, G.L., 2004. Continental basaltic rocks. In R.L. Rudnick, ed., Treatise of Geochemistry v.3, 85-121.
Ferrell, J.E., 1985. Lithium, *in*: Mineral Facts and Problems, 1985 edition, U.S. Bur. of Mines Bull. 675, 461-470.
Fersman, A.Ye., 1933. Geokhimiya. 1955 reprint, Akad. Nauk SSSR, Moscow, 798 p
Field, C.W., Rye, R.O., Dymond, J.R., et al., 1983. Metalliferous sediments of the East Pacific, *in*: W.C. Shanks III, ed, Cameron Volume on Nonconventional Mineral Deposits. AIME, New York, 133-156
Finch, W.I., 1967. Geology of epigenetic uranium deposits in sandstone in the United States. U.S. Geol. Surv. Profess. Paper 538, 121 p.
Fiorentini, M., Beresford, S., Barley, M., Duuring, P., Bekker, A., Rosengren, N., Cas, R., Hronsky, J., 2012. District to camp controls on the genesis of komatiite-hosted nickel sulfide deposits, Agnew-Wiluna greenstone belt, Western Australia: Insights from the multiple sulfur isotopes. Econ. Geol. 107, 781-796.
Fitch, D.C., 1999. Review of exploration in Mexico Part I: Copper, polymetallics, silver, VMS deposits. Mexico Mining '99, Randal Conference, Puerto Vallarta, 13 p.
Force, E.R., 1998. Laramide alteration of Proterozoic diabase, a likely contributor of copper to porphyry systems in the Dripping Springs Mountains area, southeastern Arizona. Econ. Geol. 93, 171-183.
Franklin, J.M., Gibson, H.L., Jonasson, I.R. and Galley, A.G., 2005. Volcanogenic massive sulfide deposits. Econ. Geol. 100th Anniv. Vol., 523-560.
Freyssinet, P., Butt, C.R.M., Morris, R.C. and Piantone, P., 2005. Ore-forming processes related to lateritic weathering. Econ. Geol. 100th An niv. Vol., 681-722.
Frimmel, H.E., Groves, D.I., Kirk, J., Ruiz, J. Chesley, J., Minter, W.E.L., 2005. The formation and preservation of the Witwatersrand goldfields, the World's largest gold province. Econ. Geol. 100th Anniv. Vol., 769-798.
Frimmel, H.E., 2008. Earth's continental crustal gold endowment. Earth and Planetary Science Letters 267, 1-2, 45-55.
Fundal, E., 1975. The Uivfaq dike and related hybrid dikes from southern Disko, West Greenland. Meddel. om Grønland Bd. 195, 28 p.
Garrels, R.M., Mackenzie, F.T., Hunt, C., 1975.Chemical Cycles and the Global Environment. Kaufmann, Los Angeles.
Gavshin, V.M., Zakharov, V.A., 1996. Geochemistry of the Upper Jurassic-Lower Cretaceous Bazhenov Formation, West Siberia. Econ Geol, v 91, pp 122-133.
Goad, R.E., Mumin, A.H., Duke, N.A., Neale, K.L., Mulligan, D.L., 2000. Geology of the Proterozoic iron oxide-hosted NICO cobalt-gold-bismuth, and Sue-Dianne copper-silver deposits, southern Great Bear magmatic zone, Northwest Territories, Canada, *in*: T.M. Porter, ed, Hydrothermal Iron Oxide Copper-gold and Related Deposits: A Global Perspective. AMF, Adelaide, pp 249-267.
Gold, D.P., 1963. Average chemical composition of carbonatites. Econ. Geol. 58, 988-991.
Goldfarb, R.J., Baker, T., Dubé, B., Groves, D.I., Hart, C.J.R., Gosselin, P., 2005. Distribution, character and genesis of gold deposits in metamorphic terranes. Econ. Geol. 100th Anniv. Vol., 407-450.
Goldfarb, R.J., Bradley, D., Leach, D.L., 2010. Secular variation in Economic Geology. Econ. Geol. 105, 459-465.
Goldschmidt, V.M., 1933. Grundlagen der quantitative Geochemie. Fortschr. Miner. Kristallogr., Petrogr. 17, 112 p.
Goldschmidt, V.M., 1958. Geochemistry. Oxford Univ. Press, London, 730 p.
Gow, P.A. and Walshe, J.L., 2005. The role of preexisting geologic architecture in the formation of giant porphyry-related Cu-Au deposits: Examples from New Guinea and Chile. Econ. Geol. 1000, 819-833.
Groves, D.I., Condie, K.C., Goldfarb, R.J., Hronsky, J.M.A., Vielreicher, R.M., 2005. Secular changes in global tectonic processes and their influence on the temporal distribution of gold-bearing mineral deposits. Econ. Geol. 100, 203-224.
Groves, D.I., Goldfarb, R.J., Robert, F., Hart, C.J.R., 2003. Gold deposits in metamorphic belts: Overview of current understanding, outstanding problems, future research, and exploration significance. Econ. Geol, 98, 1-29.
Gu, X.X., Zhang, Y.M., Schulz, O., Vavtar, F., Liu, J.M., Zheng, M.H., Zheng, L., 2012. The Woxi W-Sb-Au deposit in Hunan, South China: An example of Late Proterozoic sedimentary-exhalative (SEDEX) mineralization. Journ. of Asian Earth Sci. 57, 54-75.
Guj, P., Fallon, M., McCuaig, C., Fagan, R., 2011. A time-series audit of Zipf's Law as a measure of terrane endowment and maturity in mineral exploration. Econ. Geol. 106, 241-250.
Halbouty, M.T., 2003. Giant oil and gas fields of the 1990s: An introduction. Amer. Assoc. Petrol. Geol. Memoir 78, 1-13.
Halbouty, M.T., ed., 2003. Giant oil and gas fields of the decade 1990-1999. Amer, Assoc. Petrol. Geol. Memoir 78, 340 p.
Hannington, M.D., deRonde, C.E.J., Petersen, S., 2005. Sea-floor tectonics and submarine hydrothermal systems. Econ. Geol. 100th Anniv. Vol., 111-141.
Harmsworth, R.A., Kneeshaw, M., Morris, R.C., Robinson, C.J., Shrivastava, P.K., 1990. BIF-derived iron ores of the Hamersley Province, *in*: F.E. Hughes, ed, 617-642.
Harris, J.F., 1961. Summary of the geology of Tanganyika, part IV, Economic Geology. Geol. Surv. of Tanganyika, Mem. 1, 143 p.
Hauptmann, A., 2007. The Archeometallurgy of copper: evidence from Faynan, Jordan. Springer, Berlin, 388 p.
Haydon, R.C., McConachy, G.W., 1987. The stratigraophic setting of Pb-Zn-Ag mineralization in Broken Hill. Econ. Geol. 82, 826-856.
Haynes, B.W., Law, S.L., Barton, D.C., 1986. An elemental description of Pacific manganese nodules. Marine Geochemistry.
Haynes, S.D., 2006. The Olympic Dam ore deposit discovery-a personal view. SEG Newsletter 66, 1-15.
Hedenquist, J.W., Arribas, A. Jr., Reynolds, T.J., 1998. Evolution of an intrusion-centered hydrothermal system: Far Southeast-Lepanto porphyry and epithermal Cu-Au deposits, Philippines. Econ. Geol. 93, 373-404.
Hehnke, C., Ballantyne, G., Martin, H., Hart, W., Schwartz, A., Stern, H., 2012. Geology and exploration progress at the Resolution porphyry Cu-Mo deposit, Arizona. SEG Spec. Publ. 16, 147-166.
Heijlen, W., et al, 2003. Carbonate-hosted Zn-Pb deposits in Upper Silesia, Poland: Origin and evolution of mineralizing fluids and constraints of genetic models. Econ. Geol. 98, 911-932.
He Lixian, Zeng Ruolan, 1992. Mercury deposits of China, *in*: ECMDC, eds, 100-149.

Hernández, A., Jébrak, M., Higueras, P., Oyarzún, R., Morata, D., Munhá, J., 1999. The Almadén mercury mining district, Spain. Mineralium Deposita 34, 539-548.
Heyl, A.V., Agnew, A.F., Lyons, E.J., Behre, C.H. Jr., 1959. Geology of the Upper Mississippi Valley zinc-lead district. U.S. Geol. Surv. Prof. Paper 309, 310 p
Hitzman, M.W., 2011. They who see the most rocks win. SEG Newsletter 84, 12-13.
Hitzman, M.W., Broughton, D., Selley, D., Woodhead, J., Wood, D., Bull, S., 2012. The Central African Copperbelt: diverse stratigraphic, structural and temporal settings in the World's largest sedimentary copper district. SEG Spec. Publ. 16, 487-514.
Hitzman, M.W., Oreskes, N., Einaudi, M.T., 1992. Geological characteristics and tectonic setting of Proetrozoic iron oxide (Cu-U-Au-REE) deposits. Precambrian Research 58, 241-287.
Hobson, G.D., Tiratsoo, E.N., 1981. Introduction to Petroleum Geology. Gulf Publ, Houston, 252 p
Höll, R., Maucher, A., 1976. The strata-bound ore deposits in the Eastern Alps, *in*: K.H. Wolf, ed, Handbook of Stratiform and Strata-Bound Ore Deposits, v 2. Elsevier, Amsterdam, 1-36.
Holland, H.D., 2005. Sedimentary mineral deposits and the evolution of Earth's near-surface environments. Econ. Geol. 100, 1489-1509.
Hollings, P., Cooke, D.R., Waters, P.J., Cousens, B., 2011. Igneous geochemistry of mineralized rocks of the Baguio district, Philippines: Implications for tectonic evolution and the genesis of porphyry-style mineralization. Econ. Geol. 196, 1317-1333.
Hollister, V.F., ed., 1990. Case Histories of Mineral Discoveries (in 3 volumes).
Huston, D.L., 2009. Metallogeny and the evolution of the Australian continent: Linkage between mineralization and tectonic history. SGA News, No.24, 1-19.
Huston, D.L., Stevens, B., Southgate, P.N., Muhling, P., Wyborn, L., 2006. Australian Zn-Pb-Ag ore forming systems: A review and analysis. Econ. Geol. 101, 1117-1157.
Hutchinson, R.W. and Grauch, R.I., eds., 1991. Historical perspectives of genetic concepts and case histories of famous discoveries. Econ. Geol. Monograph 8, 359 p.
Jackson, N.J., Willis-Richards, J., Manning, D.A.C., Sams, M.S., 1989. Evolution of the Cornubian ore field, Southwest England; Part II. Mineral deposits and ore forming processes. Econ. Geol. 84, 1101-1133.
James, H.L., 1966. Chemistry of the iron-rich sedimentary rocks. U.S. Geol. Surv. Prof. Paper 440-W, 61 p.
Johnson, R.D., McMillan, N.J., 1993. Petroleum. Decade of North American Geology, v D-1, Geol Soc Amer, Boulder, 551-554.
Jolly, W.T., 1974. Behavior of Cu, Zn and Ni during prehnite-pumpellyite rock metamorphism of the Keweenawan basalts, northern Michigan. Econ. Geol. 69, 1118-1125.
Jones, C.B., 1990. Coppin Gap copper-molybdenum deposit, *in*: F.E. Hughes, ed, 141-144.
Kelley, D.L., Kelley, K.D., Coler, W.B., Caughlin, B., Doherty, M.E., 2006. Beyond the obvious limits of ore deposits: The use of mineralogical, geochemical and biological features for the remote detection of mineralization. Econ. Geol. 101, 729-752.
Kerr, A.C., 2004. Oceanic plateaus. In R.L. Rudnick, ed., Treatise of Geochemistry v.3, 537-565.
Kerrich, R., Goldfarb, R., Groves, D., Garwin, S., 2000. The geodynamics of world-class gold deposits: characteristics, space-time distribution, and origins. Reviews in Econ. Geol. 13, 501-551.
Kesler, S.E., Russel, N., McCurdy, K., 2003. Trace metal content of the Pueblo Viejo precious metal deposits and their relation to other high-sulfidation epithermal systems. Mineralium Deposita 38, 668-682.
Kesler, S.E. and Wilkinson, B.H., 2006. Exhumation dominates the temporal distribution of ore deposits. Econ. Geol. 101, 919-922.
Kesler, S.E. and Wilkinson, B.H., 2009. Resources of gold in Phanerozoic deposits. Econ. Geol. 104, 623-633.
Khashgerel, B-E, Rye, R.O., Kavalieris, I., Hayashi, K.I., 2009. The sericitic to advanced argillic transition: Stable isotope and mineralogical characteristics from the Hugo Dummett porphyry Cu-Au deposit, Oyu Tolgoi district, Mongolia. Econ. Geol. 104, 1087-1110.
Kirkham, R.V. and Raefer, A.B., 2003. Selected world mineral deposits database. Geol. Surv. Canada Open File 1801, 83 p. (CD-ROM).
Klemm, L.M., Pettke, T., Heinrich, C.A., Campos, E., 2007. Hydrothermal evolution of the El Teniente deposit, Chile. Porphyry Cu-Mo deposition from low salinity magmatic fluids. Econ. Geol. 102, 1021-1045.
Klett, T.R., Schmoker, J.W., 2003. Reserve growth of the world's giant ore fields. Amer. Assoc. Petrol. Geol. Memoir 78, 107-122.
Kloppenburg, A., Grocott, J., Hutchinson, D., 2010. Structural setting and synplutonic fault kinematics of a Cordilleran Cu-Au-Mo porphyry mineralization system, Bingham mining district, Utah. Econ. Geol. 105, 743-762.
Koehler, G.F. and Tikkanen, G.D., 1991. Red Dog, Alaska: Discovery and definition of a major zinc-lead-silver deposit. Econ. Geol. Monogr. 8, 268-274.
Kogarko, I.N., 1987. Alkaline rocks of the eastern part of the Baltic Shield (Kola Peninsula), *in*: J.G. Fitton, B.G. Upton, eds, Alkaline Igneous Rocks. Geol. Soc. London Spec. Publ. 30, pp 531-544.
Konofagou, K., 1980. To Archaio Laurio kai i elliniki tekhniki paragogis tou argurou. Ekdotiki/Elladoz Publishers, Athens.
Krahmann, R., 1936. The geophysical magnetometric investigation on West Witwatersrand areas between Randfontein and Potchefstroom, Transvaal. Trans. Geol. Soc. S. Africa 39, 1-44.
Kravchenko, S.M., Pokrovsky, B.G., 1995. The Tomtor alkaline ultrabasic massif and related REE-Nb deposits, northern Siberia. Econ. Geol. 90, 676-689.
Krupp, R.E., Seward, T.M., 1987. The Rotokawa geothermal system, New Zealand: An active epithermal gold-depositing environment. Econ Geol 82, 1109-1130.
Kwak, T.A.P., 1987. W-Sn Skarn Deposits and Related Metamorphic Skarns and Granitoids. Elsevier, Amsterdam, 445 p.
Kyle, J.R., 1976. Brecciation, alteration and mineralization in the Central Tennessee district. Econ. Geol. 71, 892-903.
Kyser, K., Hiatt, E., Renac, C., Durocher, K., Holk, G., Deckart, K., 2000. Diagenetic fluids in Paleo- and Meso-Proterozoic sedimentary basins and their implications for long protracted fluid histories. Miner. Assoc. Canada Short Course 28, 225-262.

Landefeld, L.A., 1988. The geology of the Mother Lode gold belt, Sierra Nevada Foothills metamorphic belt, California, *in*: G. Kisvarsanyi, S.K. Grant, eds, North American Conference on Tectonic Control of Ore Deposits, Proc., Univ. of Missouri, Rolla, pp 47-56.
Landtwing, M.R., Dillenbeck, E.D., Leake, M.H., Heinrich, C.A., 2002. Evolution of the breccia-hosted porphyry Cu-Mo-Au deposit at Agua Rica, Argentina: Progressive unroofing of magmatic-hydrothermal system. Econ. Geol. 97, 1273-1292.
Lang, J.R. and Gregory, M.J., 2012. Magmatic-hydrothermal evolution of the giant Pebble porphyry Cu-Au-Mo deposit with implications for exploration in Southwest Alaska. SEG Spec. Publ. 16, 167-186.
Langevin, P.M., Daigneault, R., Goutier, J., Dion, C., Archer, P., 2012. Geology of the Archean intrusion-hosted La-Grande-Sud Au-Cu prospect, La Grande Subprovince, James Bay region, Quebec. Econ. Geol. 107, 935-962.
Large, R.R., Bull, S.W., McGoldrick, P.J., Walters, S., Derrick, G.M., Carr, G.R., 2005. Stratiform and strata-bound Zn-Pb-Ag deposits in Proterozoic sedimentary basins, northern Australia. Econ. Geol. 100th Anniv. Vol., 931-964.
Large, R.R. et al , 2009. Gold and trace element zonation in pyrite using a laser imaging techniques: Implications for the timinng of gold in orogenic and Carlin-style sediment-hosted deposits. Econ. Geol. 106, 635-668.
Large, R.R., Bull, S.W., Maslennikov, V.V., 2011. A carbonaceous sedimentary source rock model for Carlin-type and orogenic gold deposits. Econ. Geol. 106, 331-358.
Large, R.R., Meffre, S., Burnett, R., Guy, B., Bull, S., Gilbert, S., Goeman, K., Danyushevsky, L., 2013. Evidence for an intrabasinal source and multiple concentration process in the formation of the Carbon Leader Reef, Witwatersrand Supergroup, South Africa. Econ. Geol. 108, 1215-1241.
Launay, de L., 1913. Traité de Métallogenie. Gîtes Minéraux et Metalifères. Bèranger, Paris, 3 volumes.
Laznicka, P., 1973a. MANIFILE, the University of Manitoba file of nonferrous metal deposits of the world. Centre of Precambrian Studies, Univ. of Manitoba, Winnipeg, 533 & 767 p.
Laznicka, P., 1973b. Development of non-ferrous metal deposits in geologic time. Canad. Journ. of Earth Sci, 19, 18-25.
Laznick,a P., 1983b. Giant ore deposits: A quantitative approach. Global Tectonics and Metallogeny, v 2, 41-63.
Laznicka, P., 1985ª. Empirical Metallogeny. Elsevier, Amsterdam, 1794 p
Laznicka, P., 1985b. Data on ore deposits: A critical review of their sources, acquisition, organization and presentation, *in*: K.H. Wolf, ed, Handbook of Stratiform and Stratabound Ore Deposits, v 11, 1-118.
Laznicka, P., 1992a. Manganese deposits in the global lithogenetic system: Quantitative approach. Ore Geol. Reviews, 7, 279-356.
Laznicka, P., 1993. Precambrian Empirical Metallogeny. Elsevier, Amsterdam, 1622 p.
Laznicka, P., 1999. Quantitative relationships among giant deposits of metals. Econ. Geol. 94, 455-472.
Laznicka, P., 2004. Total Metallogeny-Geosites. Austral. Mineral Foundation, Adelaide, 740 p. and poster.
Laznicka, P., 2010. Giant Metallic Depposits, Future Sources of Industrial Metals. 2nd Edition, Springer, 949 p.
Laznicka, P., 2011, 2012. Giant Metallic Deposits: Today and Tomorrow. AME-BC and MRAG Canada lecture notes, 138 p.
Laznicka, P., 2013. Giant Deposits of Metals, Today and Tomorrow. KIGAM Korea, Lecture notes, 1-265.
Leach, D.L., Sangster, D.F., Kelley, K.D., Large, R.R., Garven, G., Allen, C.R., Gutzmer, J., Walters, S., 2005. Sediment-hosted lead-zinc deposits: a global perspective. Econ. Geol. 100th Anniv. Vol., 561-608.
Leblanc, M., Morales, J.A., Borrego, J., Elbaz-Poulichet, F., 2000. 4500 years old mining pollution in southwestern Spain: Long-term implications for modern mining pollution. Econ. Geol. 95, 655-662.
Lerchbaumer, L. and Audétat, A., 2013. The metal content of silicate melts and aqueous fluids in subeconomically Mo mineralized granites: Implications for porphyry Mo genesis. Econ. Geol. 108, 987-1013.
Levitan, G., 2008. Gold deposits of the CIS. Xlibris, Philadelphia, 352 p.
Leys, C.A., Cloos, M., New, B.T.E., MacDonald, G.D., 2012. Copper-gold-molybdenum deposits of the Ertsberg-Grasberg district, Papua, Indonesia. SEG Spec. Publ. 16, 215-236.
Li N., Kyle, J.R., 1997. Geologic controls of sandstone-hosted Zn-Pb (Sr) mineralization, Jinding deposit, Yunnan Province, China: A new environment for sediment-hosted Zn-Pb deposits, *in*: Pei Rongfu, ed, 30th Intern. Geol. Congress, Beijing, Proceedings v 9, pp 67-82.
Li Yidou, 1993. Poly-type model for tungsten deposits and vertical structural zoning for vein-type tungsten deposits in South China. Geol. Assoc. Canada Spec. Paper 40, 555-568.
Lightfoot, P.C., Keays, R.R., Doherty, W., 2001. Chemical evolution and origin of nickel sulphide mineralization in the Sudbury Igneous Complex, Ontario, Canada. Econ. Geol. 96, 1855-1876.
Lightfoot, P.C. and Keays, R.R., 2005. Siderophile and chalcophile metal variations in flood basalts from the Siberian Trap, Noril'sk region: implications for the origin of the Ni-Cu-PGE sulfide ores. Econ. Geol. 100, 439-462.
Lindgren, W., 1933. Mineral Deposits, 4th edition. McGraw Hill, New York, 930 p.
Lindgren, W., Laughlin, G.F., 1919. Geology and ore deposits of the Tintic district, Utah. U.S. Geol. Surv. Profess. Paper 107, 282 p.
Livingston, D.L.,, Mauger, R.L., Damon, P.E., 1968. Geochronology of the emplacement, enrichment and preservation of Arizona porphyry copper deposits. Econ. Geol. 63, 30-36.
Long, K.R., DeYoung, J.H.Jr., Ludington, S., 2000. Significant deposits of gold, silver, copper, lead and zinc in the United States. Econ. Geol. 95, 629-644.
Longo, A.A., Dilles, J.H., Grunder, A.L., Duncan, R., 2010. Evolution of calc-alkaline volcanism and associated hydrothermal gold deposits at Yanacocha, Peru. Econ. Geol. 105, 1191-1241.
Loukola-Ruskeeniemi, K. 1991. Mercury concentrations in Proterozoic black schists in Finland: Environmental and Exploration aspects, *in*: M. Pagel et al, eds., Source, Transport and Deposition of Metals. Balkema, Rotterdam, pp 557-560.
Love, D.A., Clark, A.H., Glover, J.K., 2004. The lithologic, stratigraphic, and structural setting of the giant Antamina copper-zinc skarn deposit, Ancash, Peru. Econ. Geol. 99, 887-916.

Lowell, J.D., 1991. The discovery of the La Escondida orebody. Econ. Geol. Monogr. 8, 300-313.

Lowell, J.D., Guilbert, J.M., 1970. Lateral and vertical alteration-mineralization zoning in porphyry copper ore deposits. Econ. Geol. 65, 373-408.

Lowther, J.M., 1994. Mahd adh Dhahab gold deposit. Directorate General of Mineral Resources, Jeddah, Spec. Publ. 2, 105-111.

Lu Huan-Zhang, et al., 2003. Mineralization and fluid inclusion study of the Shizhouyuan W-Sn-Bi-Mo-F skarn deposit, Hunan Province, China. Econ. Geol. 98, 955-974.

Machamer, J.F., Tolbert, G.E., L'Esperance, R.L., 1991. The discovery of Serra dos Carajás. Econ. Geol. Memoir 8, 275-285.

Mao, J., Lehmann, B., Du, A., Zhang, G., Ma, D., Wang, Y., Zeng, M., Kerrich, R., 2002. Re-Os dating of polymetallic Ni-Mo-PGE-Au mineralization in Lower Cambrian black shales of South China and its geologic significance. Econ. Geol. 97, 1051-1061.

Marlatt, J.L. and Kyser, T.K., 2011. Paradigmatic shifts in the uranium exploration process: knowledge brokers and the Athabasca Basin learning curve. SEG Newsletter 84, 1-23.

Marquis, P., Brown, A.C., Hulbert, C., Rigg, D.M., 1990. Progressive alteration associated with auriferous massive sulfide bodies at the Dumagami Mine, Abitibi greenstone belt, Quebec. Econ. Geol. 85, 746-764.

Marsden, R.W. et al., 1968. The Mesabi Iron Range, Minnesota, *in*: J.D. Ridge, ed,, Ore Deposits in the United States 1933-1967, AIME, pp 518-537.

Masong, T.,Jr. and Arndt, R.E., 1996. Mineral Resources Data System (MRDS). U.S. Geol. Surv. Digital Data Series 20 (CD-ROM).

Maynard, J.B., 2010. The chemistry of manganese ores through time: A signal of increasing diversity of Earth-surface environments. Econ. Geol. 105, 535-552.

McKelvey, V.E., Strobell, J.D. Jr., Slaughter, A.L., 1986. The vanadiferous zone of the Phosphoria Formation in western Wyoming and southeastern Idaho. U.S. Geol. Surv. Prof. Paper 1465, 27 p.

McKibben, M.A., Andes, J.P. Jr., Williams, A.E., 1988. Active ore formation at a brine interface in metamorphosed deltaic lacustrine sediments: The Salton Sea geothermal system, California. Econ. Geol. 83, 511-523.

Mealey, G.A., 1996. Grasberg. Mining the Richest and Most Remote Deposit of Copper and Gold in the World, in the Mountains of Irian Jaya, Indonesia. Freeport McMoRan Inc, New Orleans, 384 p.

Meinert, L.D., Dipple, G.M., Nicolescu, S., 2005. World skarn deposits. Econ. Geol. 100th Anniv. Vol., 299-336.

Miller, R.R., 1988. Yttrium (Y) and other rare metals (Be, Nb, REE, Ta, Zr) in Labrador. Newfoundland Dept. of Mines Rept. 88-1, pp 229-245.

Minter, W.E.L., Hill, W.C.N., Kidger, R.J., Kingsley, C.S., Snowden, P.A., 1986. The Welkom Goldfield, *in*: C.R. Anhaeusser, S. Maske, eds, pp 497-539.

Morey, G.B., 1999. High-grade iron ore deposits of the Mesabi Range, Minnesota-product of a continental-scale Proterozoic ground-water flow system. Econ. Geol. 94, 133-142.

Morrison, G.G., 1984. Morphological features of the Sudbury Structure in relation to an impact origin, *in*: E.G. Pye et al, eds,, The Geology and Ore Deposits of the Sudbury Structure. Ontario Geol. Surv. Spec. Vol. 1, 603 p.

Mudd, G.M., Weng, Z., Jowitt, S.H., 2013. A detailed assessment of global Cu resource trends and endowments. Econ. Geol. 108, 1163-1183.

Muessig, S., 2011. Some elements of exploration success or how to shave the odds. SEG Newsletter 87, 10-12.

Muntean, J. and Taufen, P., 2011. Geochemical exploration for gold through transported alluvial cover in Nevada; Examples from the Cortez Mine. Econ. Geol. 106, 809-834.

Mutschler, F.E., Ludington, S., Bookstrom, A.A., 2000. Giant porphyry-related metal camps of the world: a database. U.S. Geol. Surv. Open File Report 99-556.

Naldret,t A.J., Fedorenko, V.A., Asif, M. et al., 1996. Controls on the composition of Ni-Cu sulfide deposits as illustrated by those at Noril'lsk, Siberia. Econ. Geol. 91, 751-773.

Nelson, M., Kyser, K., Clark, A., Oates, C., 2007. Carbon isotope evidence for microbial involvement in exotic copper silicate mineralization, Huinquintipa and Mina Sur, Northern Chile. Econ. Geol. 102, 1311-1320.

Nielsen, B.L., 1973. A survey of the economic geology of Greenland (exclusive fossil fuels). Grønl. Geol. Unders., Rapp. Nr 56, 45 p.

Noble, D.C., Vidal, C.E., 1990. Association of silver with mercury, arsenic, antimony and carbonaceous material at the Huancavelica district, Peru. Econ. Geol. 85, 1645-1650.

Okita, P.M., 1992. Manganese carbonate mineralization in the Molango district, Mexico. Econ. Geol. 87, 1345-1366.

Oppenheimer, C., 2004. Volcanic degassing, in: R.L. Rudnick, ed., Treatise of Geochemistry, v.3, 123-166.

Orth, C.J., Attrep, M., Quintana, L.R., Elder, W.P., Kauffman, E.G., Diner, R., Villamil, T., 1993. Elemental abundance anomalies in the late Cenomanian extinction interval: A search for the source(s). Earth Planet. Sci. Letters 117, 189-204.

Ossandón, G.C., Fréraut, R.C., Gustafson, L.B., Lindsay, D.D., Zentilli, M., 2001. Geology of the Chuquicamata Mine: A progress report. Econ. Geol. 96, 249-270.

Oyuarzún, R., Marquez, A., Lillo, J., Lopez, I., Rivera, S., 2001. Giant versus small porphyry copper deposits of Cenozoic age in northern Chile: Adakitic versus normal calc-alkaline magmatism. Miner. Deposita 36, 794-798.

Padilla, R.A.G., Titley, S.R., Pimentel, F.B., 2001. Geology of the Escondida porphyry copper deposit, Antofagasta region, Chile. Econ. Geol. 96, 307-324.

Palme, H. and O'Neill, H., St.C., 2004. Cosnochemical estimates of mantle composition, in: R.W. Carlson, ed., Treatise on Geochemistry v.2, 1-38.

Paone, J., 1970. Germanium, *in*: Mineral Facts and Problems. U.S. Bur. of Mines Bull. 650, 563-571.

Parker, H.M. et al., 2013. Ivanplats Limited, Kamoa Copper Project. NI 43-101 Technical report on updated mineral resource estimate. www.ivanplats.com.

Patchett, P.J. and Samson, S.D., 2004. Ages and growth of the continental crust from radiogenic isotopes, in: R.K. Rudnick, ed., Treatise of Geochemistry v.3, 321-348.

Perelló, J., Sillitoe, R.H., Mpodozis, C., Brockway, H., Posso, H., 2012. Geologic setting and evolution of the porphyry copper-molybdenum and copper-gold deposits at Los Pelambres, Central Chile. SEG Spec. Publ. 16, 79-104.

Perkins, W.G., 1997. Mount Isa lead-zinc orebodies: Replacement lodes in a zoned syndeformational copper-lead-zinc system? Ore Geol. Reviews 12, 61-111.

Pichler, H., 1970. Italianische Vulkan-Gebiete I (Somma-Vesuv, Latium, Toscana). Borntraeger, 258 p.

Piper, D.Z.,, Hatch, G.R., 1989. Hydrogenous sediment, *in*: The Geology of North America, vol N. Geol. Soc. Amer,, Boulder, pp 337-345

Pirajno, F., 2001. Ore Deposits and Mantle Plumes. Kluwer Acad. Publ., Dordrecht, 576 p.

Pirajno, F., 2004. Hotspots and mantle plumes: global intraplate tectonics, magmatism and ore deposits. Miner. Petr. 82, 183-216.

Pirajno, F., 2013, The Geology and Tectonic Settings of China's Mineral Deposits. Springer, 679 p.

Pollard, P.J., Taylor, R.G., Peters, L., 2005. Ages of intrusion, alteration and mineralization at the Grasberg Cu-Au deposit, Papua, Indonesia. Econ. Geol. 100, 1005-1020.

Prevec, S.A. and Cawthorn, R.G., 2002. Thermal evolution and interaction between impact melt sheet and footwall: A genetic model for the contact sublayer of the Sudbury Igneous Complex, Canada. Journ. Geophys. Res. 107, 2176-2198.

Price, J.G., 2004. I never met a rhyolite I didn't like-some of the geology in economic geology. SEG Newsletter, 57, pp 1+10-13.

Price, J.G., Rubin, J.N., Henry, C.D., Pinkston, T.L., Tweedy, S.W., Koppenaal, D.W., 1990. Rare-metal enriched peraluminous rhyolites in a continental arc, Sierra Blanca area, Trans-Pecos Texas; chemical modification by vapor-phase crystallization. Geol. Soc. Amer., Spec. Paper 246, 103-120.

Proffett, J.M., 2003. Geology of the Bajo de la Alumbrera porphyry copper-gold deposit, Argentina. Econ. Geol. 98, 1535-1574.

Proffett, J.M., 2010. High Cu-grades in porphyry Cu deposits and their relationship to emplacement depth of magmatic sources. Geology 37, 675-678.

Reed, M., Rusk, B., Palandri, J., 2013. The Butte magmatic-hydrothermal system: One fluid yields all alteration and veins. Econ. Geol. 108, 1379-1396.

Relvas, J.M.R.S., Barriga, F.J.A.S., Ferreira, A., Noiva, P.C., Pacheco, N., Barriga, G., 2006. Hydrothermal alteration and mineralization in the Neves-Corvo volcanic-hosted massive sulfide deposit, Portugal: I. Geology, mineralogy and geochemistry. Econ. Geol. 101, 753-790.

Rice, C.M., Steele, G.B., Barfod, D.N., Boyce, A.J., Pringle, M.S., 2005. Duration of magmatic, hydrothermal and supergene activity at Cerro Rico de Potosi, Bolivia. Econ. Geol. 100, 1647-1656.

Richards, J.P., 2003. Tectono-magmatic precursors for porphyry Cu-(Mo-Au) deposit formation. Econ. Geol. 98, 1515-1533.

Richards, J.P., 2011. High Sr/Y arc magmas and porphyry Cu-Mo-Au deposits: Just add water. Econ. Geol. 106, 1075-1082.

Richards, J.P., Boyce, A.J., Pringle, M.S., 2001. Geologic evolution of the Escondida area, northern Chile: A model for spatial and temporal localization of porphyry Cu mineralization. Econ. Geol. 96, 271-305.

Richards, J.P. and Kerrich, R., 2007. Adakite-like rocks: Their diverse origins and questionable role in metallogenesis. Econ. Geol. 102, 537-576.

Rivera, S.L., Alcota, H., Proffett, J., Diaz, J., Leiva, G., Vergana, M., 2012. Update of the geologic setting and porphyry Cu-Mo deposits in the Chuquicamata district, northern Chile. SEG Spec. Publ. 16, 19-54.

Rock, N.M.S., ed., 1991. Lamprophyres. Blackie, Glasgow.

Roscoe, S.M., 1996. Paleoplacer uranium, gold, *in*: O.R. Eckstrand et al, eds, Geology of Canada No 8. Geol. Surv. Canada, pp 10-23.

Roy, P.S., Whitehouse, J., Cowell, P.J., Oakes, G., 2000. Mineral sands occurrences in the Murray Basin, southeastern Australia. Econ. Geol. 95, 1107-1128.

Rudnick, R.L., Gao, S., 2004. Composition of the continental crust, *in*: Rudnick, R.L., ed, pp 1-64.

Rusk, B.G., Reed, M.H., Dilles, J.H., 2008. Fluid inclusion evidence for magmatic-hydrothermal fluid evolution in the porphyry copper-molybdenum deposit at Butte, Montana. Econ. Geol. 103, 307-334.

Russkikh, S.S., Shatov, V.V., 1996. The Verkhnee Qairaqty scheelite stockwork deposit in Central Kazakhstan, *in*: V.V. Shatov et al., eds., Granite-related ore deposits of Central Kazakhstan and adjacent areas. Glagol, St. Petersburg, pp 167-180.

Rytuba, J.J., Glanzman, R.K., 1985. Relation of mercury, uranium and lithium deposits to the McDermitt caldera complex, Nevada-Oregon, *in*: V.F. Hollister, ed., Discovery of Epithermal Precious Metal Deposits. AIME, pp 128-135.

Said, R., 1962. The Geology of Egypt. Elsevier, 377 p.

Sangster, D.F., 1972. Precambrian volcanogenic massive sulfide deposits in Canada: A review. Geol. Surv. Canada Paper 77-22, 44 p.

Saunders, A. and Tarney, J., 1991.Back-arc basins, *in*: P.A. Floyd, ed, Oceanic Basalts. Blackie & Van Nostrand Reinhold, pp 219-263.

Saunders, A.D., Tarney, J., Stern, C.R., Dalziel, I.W.D., 1979. Geochemistry of Mesozoic marginal basin floor igneous rocks from southern Chile. Geol. Soc. Amer. Bull, Part I, v 90, 237-258.

Schmandt, D., Broughton, D., Hitzman, M.W., Plink-Bjorklund, P., Edwards, S.D., Humphrey, J., 2013. The Kamoa copper deposit, Democratic Republic of Congo: Stratigraphy, diagenetic and hydrothermal alteration, and mineralization. Econ. Geol. 108, 1301-1324.

Schneiderhöhn, H., 1955. Erzlagerstätten, 3rd Ed. Fischer, Jena, 858 p.

Schodde, R. and Hronsky, J.M.A., 2006. The role of world-class mines in wealth creation. SEG Spec. Publ. 12, 71-90.

Schutte, P., Chiaradia, M., Beaty, B., 2010. Petrogenetic evolution of arc magmatism associated with Late Oligocene to Late Miocene porphyry-related ore deposits in Ecuador. Econ. Geol. 105, 1243-1270.

Schwartz, M.O. and Askury, A.K., 1989. Geologic, geochemical and fluid inclusion studies of the tin granites from the Bujang Melaka Pluton, Kinta Valley, Malaysia. Econ. Geol. 84, 751-779.

Sharpe, J.L., 1965. Field relations of Matagami sulphide masses bearing on their deposition in time and space. Canad. Inst. Min. Metall. Petrol. Trans. 68, 265-278.

Sheth, H.C., 2007. "Large Igneous Provinces (LIPs)": Definition, recommended terminology and a hierarchical classification. Earth Sci. Reviews 85, 117-124.

Shikazano, N., 1975. Mineralization and chemical environment of the Toyoha lead-zinc vein type deposits, Hokkaido, Japan. Econ. Geol. 70, 694-705.

Sillitoe, R.H., 2008. Major gold deposits and belts of the North and South American Cordillera: Distribution, tectonomagmatic settings, and metallogenic considerations. Econ. Geol. 103, 663-687.

Sillitoe, R.H. 2010a. Porphyry copper syustems. Econ. Geol. 105, 3-41.

Sillitoe, R.H., 2010b. Exploration and discovery of base and precious metal deposits in the Circum-Pacific region-a 2010 perspective. Resource Geology Spec. Issue 22, 139 p.

Sillitoe, R.H. and Mortensen, J.K., 2010. Longevity of porphyry copper formation at Quellaveco, Peru. Econ. Geol. 105, 1157-1162.

Sillitoe, R.H. and Perelló, J., 2005. Andean copper province: tectonomagmatic setting, deposit types, metallogeny, exploration, and discovery. Econ. Geol. 100th Anniv. Vol., 845-890.

Simons, S.F. and Brown, K.L., 2007. The flux of gold and related metals through a volcanic arc, Taupo volcanic zone, New Zealand. Geology 35, 1099-1102.

Singer, D.A., 1995. World class base and precious metal deposits: A quantitative analysis. Econ. Geol. 90, 88-104.

Singer, D.A., Berger, V.I., Menzie, W.D., Berger, B.R., 2005. Porphyry copper deposit density. Econ.Geol. 100, 491-514.

Singer, D.A., Berger, V.I., Moring, B.C., 2002. Porphyry copper deposits of the world-database, maps, and preliminary analysis. U.S. Geol. Survey Open File Rept. 02-268.

Singer, D.A., Berger, V.I., Moring, B.C., 2008. Porphyry copper deposits of the world-database and grade and tonnage models. U.S. Geol. Survey Open File Report 2008-1155.

Skarpelis, N. and Argyraki, A., 2009. Geology and origin of supergene ore at the Lavrion Pb-Zn-Ag deposit, Attica, Greece. Resource Geology 59, 1-14.

Skewes, M.A. and Stern, C.R., 1995. Genesis of the giant Late-Mioicene to Pliocene copper deposits of Central Chile in the context of Andean magmatic and tectonic evolution. Intern. Geol. Rev. 37, 893-909.

Smith, J.L., 2012. On the portents of peak oil (and other indicators of resource scarcity). Energy Policy 44, 68-78.

Smith, J.W., Milton, C., 1966. Dawsonite in the Green River Formation of Colorado. Econ. Geo. 61, 1029-1042.

Snowden Ltd., 2012. Brucejack Project, Mineral Resources Update Technical report. 106 p., www.pretium.com.

Sokolov, G.A., Grigor'ev, V.M., 1974. Deposits of iron, *in*: V.I. Smirnov, ed, Ore Deposits of the USSR, v.1. Engl. transl., Pitman, London, pp 7-113.

Solomon, M., Groves, D.I., Jaques, A.L., 1994. The Geology and Origin of Australia's Mineral Deposits. Clarendon Press, Oxford, 951 p.

Sperling, H., Walcher, E., 1990 Die Blei-Zink-Erzlagerstätte Rammelsberg (ausgenommen Neues Lager). Geol. Jahrb, v. D91, pp 3-153.

Staatz, M.H., 1979. Geology and mineral resources of the Lemhi Pass thorium district, Idaho and Montana. U.S. Geol. Surv. Profess. Paper 1049-A.

Štemprok, M., Pivec, E., Lang, M., Novák, J.K., 1995. Phosphorus in the younger granites of the Krušné Hory (Erzgebirge) Batholith, *in*: J. Pašava et al., eds., Mineral Deposits, from their Origin to their Environmental Impacts. Balkema, Rotterdam, pp 535-537.

Swanson, V.E., 1961. Geology and geochemistry of uranium in marine black shales, a review. U.S. Geol. Surv. Prof.Paper 356-C, 67-112.

Symons, P.M., et al., 1990. Boddington gold deposit, *in*: F.E. Hughes, ed, pp 165-170.

Tanelli, G., Lattanzi, P., 1985. The cassiterite-polymetallic sulfide deposits of Dachang (Guangxi, People's Republic of China). Mineralium Deposita 20, 102-106.

Tarkhanov, A.V., et al., 1991. Zheltorechenskoe vanadii-skandievoye mestorozhdeniye. Geol. Rud. Mestor., v 6, pp 50-56.

Taylor, D.H., 1998. Ballarat gold deposits, in: D.A. Berkman and D.H. Mackenzie, eds., Geology of Australian and Papua New Guinean Mineral Deposits. AusIMM, Melbourne, 543-548.

Taylor, S.R., McLennan, S.M., 1985. The Continental Crust: Its Composition and Evolution. Blackwell.

Taylor, S.R., McLennan, S.M., 1995. The geological evolution of the continental crust. Reviews of Geophysics, 33, 241-265.

Teal, L. and Benavides, A., 2010. History and geologic overview of the Yanacocha mining district, Cajamarca, Peru. Econ. Geol. 105, 1173-1190.

Temple, A.K., Grogan, R.M., 1965. Carbonatite and related alkalic rocks at Powderhorn, Colorado. Econ. Geol. 60, 672-692.

Theodore, T.G. et al., 2003. Applied geochemistry, geology and mineralogy of the northernmost Carlin Trend, Nevada. Econ. Geol. 98, 287-316.

Thomas, H.V., Large, R.R., Bull, S.W., Maslennikov, V., Berry, R.F., Fraser, R., Froud, S., Moye, R., 2011. Pyrite and pyrrhotite textures and compposituion in sediments, laminated quartz veins, and reefs at Bendigo gold mine, Australia. Insights for ore genesis. Econ. Geol. 106, 1-31.

Tomskaya Kompleksnaya Ekspeditsia, 1964. Zapadno-Sibirskii zhelezorudnyi bassein. AN SSSR, Novosibirsk, 350 p.

Toro, J.C., Ortuzar, J., Zamorano, J., Cuadra, P., Hermosilla, J., Spröhnle, C., 2012. Protracted magmatic-hydrothermal history of the Rio Blanco-Los Bronces district, Central Chile: Development of World's greatest known concentration of copper. SEG Spec. Publ. 16, 105-126.

Trueman, D., 1983 Geology of the Thor Lake area. Northern Miner, Jan 19, pp. B29-B30.

Tsikos, H., Beukes, N.J., Moore, J.M., Harris, C., 2003. Deposition, diagenesis and secondary enrichment of metals in the Paleoproterozoic Hotazel Iron Formation, Kalahari manganese field, South Africa. Econ. Geol 98, 1449-1462.

Tukiainen, T., 1988. Niobium-tantalum mineralization in the Motzfeldt Centre of the Igaliko nepheline syenite complex, South Greenland, *in*: J. Boissonvas, P. Omenetto, eds, Mineral Deposits Within the European Community. Springer-Verlag, pp 230-246.

Turneaure, F.S., 1955. Metallogenic provinces and epochs. Econ. Geol. 50th Anniv. Vol., 38-99.

United Nations, 1990. Atlas of mineral resources of the ESCAP region, Volume 6, Viet Nam. Explanation Brochure, Bangkok, 124 p.

U.S. Geol. Survey Minerals Team, 1996. Data base for a national mineral-resource assessment of undiscovered deposits of gold, silver, copper, lead and zinc in conterminous United States. USGS Open File Report 96-96, CD-ROM.

Vallée, M., Raby, R., 1971. The Magpie titaniferous magnetite deposit. CIM. Transactions, v. 74, pp 264-271.

Varentsov, I.M., Rakhmanov, V.P., 1974. Deposits of manganese, *in*: V.I. Smirnov, ed,, Ore Deposits of the USSR, v 1. Engl. Transl., Pitman, London, pp 114-178.

Velador, J.M., Heizler, M.T., Campbell, A.R., 2010. Timing of magmatic activity and mineralization and evidence of a long-lived hydrothermal system in the Fresnillo silver district, Mexico: Constrained by $^{40}Ar/^{39}Ar$ geochronology. Econ. Geol. 105, 1335-1350.

Vlasov, K.A., Kuzmenko, M.Z., Yeskova, Ye.M., 1959. The Lovozero Alkalic Massif. Engl. transl, Oliver & Boyd, Edinburgh, 627 p.

Vry, V.H., Wilkinson, J.J., Seguel, J., Millan, J., 2010. Multistage intrusion, brecciation and veining at El Teniente, Chile: Evolution of a nested porphyry system. Econ. Geol. 106, 119-153.

Wager, L.R. and Mitchell, R.L., 1951. The distribution of trace elements during strong fractionation of basic magma: A further study of the Skaergaard intrusion, East Greenland. Geoch. Cosmoch. Acta 1, 129-208.

Wallace, S.R., 1995. Presidential address: The Climax-type molybdenite deposits: What they are, where they are, and why they are. Econ. Geol. 90, 1359-1380.

Waters, P.J., Cooke, D.R., Gonzales, R.I., Phillips, D., 2011. Porphyry and epithermal deposits and $^{40}Ar/^{39}Ar$ geochronology of the Baguio district, Philippines. Econ. Geol. 106, 1335-1363.

Wedepohl, K.H., 1995. The composition of the continental crust. Geoch Cosmoch Acta 59, 1217-1232.

Weihed, J.B., Bergstrom, U., Billstrom, K., et al., 1996. Geology, tectonic setting, and origin of the Paleoproterozoic Boliden Au-Cu-As deposit, Skellefte district, northern Sweden. Econ. Geol.91, 1073-1097.

White. W.H., Bookstrom, A,A., Kamilli, R.J., et al., 1981. Character and origin of Climax-type molybdenum deposits. Econ. Geol. 75th Anniv Vol., 270-316.

Wilde, A.R., Layer, P., Mernagh, T., Foster, J., 2001. The giant Muruntau gold deposit. Geologic, geochronologic, and fluid inclusion constraints on ore genesis. Econ. Geol. 96, 633-644.

Willis, G.F. and Tosdal, R.M., 1992. Formation of gold veins and breccias during dectral strike-slip faulting in the Mesquite mining district, south-eastern California. Econ. Geol. 87, 2002-2022.

Wilkinson, B.H. and Kesler, S.E., 2010. Tectonic-diffusion estimate of orogenic gold resources. Econ. Geol. 105, 1321-1334.

Willman, C.E., Korsch, R.J., Moore, D.H., Cayley, R.A., Lisitsin, V.A., Rawling, T.J., Morand, V.J., O'Shea, P.J., 2010. Crustal scale fluid pathways in the Victorian gold province, Australia: Insights from deep seismic reflection profiles. Econ. Geol. 105, 895-915.

Wilson, C.J.L., Schaubs, P.M., Leader, L.D., 2013. Mineral precipitation in the quartz reefs of the Bendigo deposit, Victoria, Australia. Econ. Geol. 108, 259-278.

Wood, D., 2012. Discovery of the Cadia deposit, NSW, Australia, Part 1. SEG Newsletter 88, 1-22.

Wooden, J.L., Czamanske, G.K., Fedorenko, V.A., Arndt, N.T., Chauvel, C., Bouse, R.M., King, B.W., Knight, R.J., Siems, D.F., 1993. Isotopic and trace element constraints on mantle and crustal contributions to Siberian continental flood basalts, Noril'sk area, Siberia. Geoch. Cosmoch. Acta 57, 3677-3704.

Woolley, A.R., 1989. The spatial and temporal distribution of carbonatites, *in*: K. Bell, ed, Carbonatites-Genesis and Evolution. Unwin Hyman, London, pp 149-176.

Wu Jiada, Xiao Qiming, Zhao Shougeng 1990. Antimony deposits of China, *in*: Mineral Deposits of China, v.1, Geol Publ House, Beijing, pp 209-287.

Wysoczanski, R.J., Handler, M.R., Schipper, C.I., Leybourne, M.I., Creech, J., Rotella, M.D., Nichols, A.R.L., Wilson, C.J.N., Stewart, R.B., 2012. The tectonomagmatic source of ore metals and volatile elements in the southern Kermadec Arc. Econ. Geol. 107, 1539-1556.

Yakubchuk, A., Degtyarev, K., Maslennikov, V.V., Wurst, A., Stekhin, A., Lobanov, K., 2012. Tectonomagmatic setting, architecture and metallogeny of the Central Asian copper province. SEG Spec. Publ. 16, 403-432.

Zheng Yaxin, 1992. The rare alkali metal characteristics of Tibetian geothermal systems and the potential for exploitation and utilization, in: Kharaka and Maest, eds., Water-Rock Interaction. Balkema, Rotterdam, 1379-1386.

Appendix: Explanations of country codes

Appendix: Explanations of country codes

AF	Afghanistan	GY	Guyana	NM	Namibia
AG	Algeria	HU	Hungary	PE	Peru
AM	Armenia	IA	India	PH	Philippines
AR	Argentina	ID	Indonesia	PK	Pakistan
AS	Austria	IN	Iran	PL	Poland
AU	Australia	IR	Ireland	PT	Portugal
BL	Bulgaria	IS	Israel	RO	Romania
BM	Burma	IT	Italy	RS	Russia
BO	Bolivia	IV	Ivory Coast	SA	South Africa
BR	Brazil	JA	Jamaica	SB	Saudi Arabia
BW	Botswana	JP	Japan	SER	Serbia
CG	Congo (DRC)	KO	The Koreas	SK	Slovakia
CH	China	KS	Kyrgyzstan	SL	Sierra Leone
CL	Chile	KV	Kosovo	SM	Solomon Islands
CN	Canada	KZ	Kazakhstan	SP	Spain
CO	Colombia	LI	Liberia	SR	Sri Lanka
CY	Cyprus	LX	Luxembourg	SU	Suriname
CZ	Czech Republic	MA	Madagascar	SV	Slovenia
DR	Dominican Republic	MD	Macedonia	SW	Sweden
EC	Ecuador	MI	Mali	TA	Tajikistan
EG	Egypt	ML	Malaysia	TH	Thailand
FJ	Fiji	MO	Mongolia	TK	Turkey
FN	Finland	MR	Morocco	TU	Tunisia
FR	France	MU	Mauritania	TW	China-Taiwan
GA	Georgia	MX	Mexico	TZ	Tanzania
GB	Great Britain	NC	New Caledonia	UK	Ukraine
GE	Germany	NG	Nigeria	US	United States
GH	Ghana	NR	Niger	UZ	Uzbekistan
GL	Greenland	NW	Norway	VE	Venezuela
GN	Guinea	PNG	Papua New Guinea	VI	Vietnam
GO	Gabon	NZ	New Zealand	ZA	Zambia
GR	Greece	PA	Panama	ZB	Zimbabwe

TEXT FOR FIGURES

Fig.1.1. Ancient gold workings in the Arabian Shield go back two to three millennia and more: Gohafah, center and bottom left; Hamdan, bottom right. Several tens of such workings now registered with the Saudi Arabian Geological Survey provide ready sites to explore. Bottom right: Hand-excavated mining tunnels from the Roman era (around 100 A.D.) in Roşia Montană, Romania, followed high-grade epithermal veins. Laznicka, 2012.

Fig. 2.1. Giant deposits are not qualitatively unique, but just the quantitatively highest members of a progression of lesser deposits as shown for porphyry coppers. Basic type characteristics at the super-giant Bingham Canyon deposit (>50 Mt Cu, top left) are comparable with those at the <50 Kt Cu Ruddygore deposit in Queensland. Laznicka, 2012.

Fig.2.2. Historical increase of metal endowment at five super-giant copper deposits and one gold deposit. In the four Cu deposits discovered before 1900 the increase is due to steady addition of ore reserves through continuing exploration and lowering of grade. The two deposits discovered in the 1970s and 1980s have grown rapidly within two decades after mining startup. Laznicka, 2013.

Fig. 2.3. “Footprint” (geographic dimension) of the various mineralized objects with example localities (database entries). The abbreviations and details are provided in Table 2.4. Laznicka (2012)

Fig. 3.1. Graph showing numbers of giant and super-giant metal accumulations, plotted from a 2012 database. Most “metal accumulations” come from a single deposit, although some (super) deposits comprise up to five giant metal accumulations (Olympic Dam-5). Laznicka, 2012.

Fig. 3.2. The complicated path from idea to operating mine is expressed graphically by a series of initiatives (shown as black columns) progressing against a series of problems that have to be overcome, or the effort terminated. The yellow territory represent geological factors, the red political, economic and environmental factors. Starting from bottom right the first short black column represents an initiative that was shortly terminated as the area was not geologically promising. The second column from the right is about an initiative terminated because of unacceptable politico-economic risk. Moving to the left, black columns increasing in length, show variable success in reaching the final goal of establishing a mine, achieved with the last column on left. Laznicka, 2013.

Fig. 3.3. Politico-environmental considerations won over economic-geological ones with closure of two uranium deposits in two former socialist countries (East Germany and Czechoslovakia) after political changes in 1989-1991. In both cases close to 100,000 t U has been entombed for reason of environmental protection. Laznicka, 2012.

Fig. 4.1. Graphic representation of a well understood system of ore formation (Ni-laterite & saprolite) showing the variable importance of system components to produce an economic orebody. The system to operate requires as a #1 condition presence of an ultrabasic parent rock with high trace Ni, as well as humid tropical conditions and suitable physiography. Once formed, the deposit has to be protected from removal by erosion. Laznicka, 2010.

Fig.4.2. An engineered, fully optimized industrial processing system at Olympic Dam, South Australia, designed to incrementally increase concentration of metals (in this case of Cu, U, Au) from ore (=geologically metal pre-enriched input material) to obtain the final product like 99.9% Cu electrolytic copper. Geological ore-forming systems comprise similar stages leading to ore formation out of dispersed trace metals in rocks, melts and fluids, but are largely inefficient and wasteful. Courtesy of the WMC Corporation, 1990.

Fig. 4.3. Geological models, initially empirical (based on observed or analysed facts), then increasingly conceptual, became an important aid in planned exploration after 1960. The “unconformity uranium” model attributed to Duncan Derry and first conceived along the eastern margin of the Athabasca Plateau in Saskatchewan, provided an important exploration lead applied internationally, especially in Canada and Australia. Partial explanations: 1-3 units are flat-

lying Mesoproterozoic sandstone units, 5-8 are Paleoproterozoic basement metamorphic rocks. The U mineralization comes as sandstone infiltrations above unconformity (M), and as uraninite masses along basement faults (N, S). They are controlled by unconformity floored by paleoregolith. Ore outcrops are confined to a narrow zone outside the sandstone plateau escarpment as farther away the shallow deposits have been removed by erosion. Laznicka, 2001.

Fig. 4.4. Inventory of metals in lithosphere and hydrosphere on the example of manganese. Most metals are stored in "rocks", approaching Clarke concentration, with only a fraction accumulated in high-grade materials called ores (right-hand side of the graph). As the highest-grade ores (45-65% Mn here) are being rapidly exhausted, the exploitation moves into progressively lower-grade materials, limited by economic conditions of the day. Should the "ores" be ever exhausted, mining will move into "rocks". As industrial production of metals is governed by economics (especially commodity prices), it is possible to extract metals from very low-grade materials like sea-water (Mg), when it is economically feasible. Such materials are shown on the left-hand side of the graph. The two troughs in the graph: one between "ores" and "rocks", the other between "rocks" and "waters" are most likely caused by the lack of analytical data than by geological conditions, where a Gaussian curve would more likely apply. Modified from Laznicka, 1992.

Fig. 4.5. Graph of incremental increase of concentration of selected metals, in four successive stages, leading to economic deposits in three geological settings as described in Table 4.2. Laznicka, 2013.

Fig. 4.6. Unmined rare metals deposit Ghurayyah (the small brown hill in the centre), in the north-western corner of the Arabian Shield. This is a stock of Lower Paleozoic peralkaline granite (4+M in the cross-section, emplaced to Neoproterozoic metamorphic rocks=5; corresponding rock samples are shown on right), with finely disseminated minerals of Zr, Y, Th, Ta, Nb and U. Future exploitation will have to solve the problem of what to do with the low-demand metals like Y and Th. Laznicka, 2012, also in www.datametallogenica.com, No. 2171.

Fig. 4.7. Graphic representation of the model of Thomas et al. (2011) that attributes the gold source in Bendigo gold-quartz lodes to black shale horizons in the host Ordovician turbidites (four samples in bottom row). Wilson et al. (2013), however, put the gold source into Cambrian mafic volcanic rocks in depth. The "lithotheque" set on the left shows the ore varieties, evolving from quartz ribbons alternating with wallrock slivers to massive quartz. Laznicka (2012), also in www.datametallogenica.com.

Fig. 5.1. Graph of pre-1900 discovery periods of significant metallic deposits listed in Table 5.1. Each square represents one deposit of dominant metal. Laznicka, 2013

Fig. 5.2. Graph of post-1900 discovery periods of significant metallic deposits listed in Table 5.1. Each square represents one deposit of dominant metal. Laznicka, 2013.

Fig. 5.3. Kalgoorlie (Western Australia) Superpit, a system of gold-quartz veins and stockworks in Archean diabase, and (bottom right) statue of Patrick Hannan, the discoverer. Laznicka, 2012.

Fig. 5.4. From medieval European "world class" to American baroque "giant" silver deposits. Top left is the former mint in Jáchymov (Joachimsthal), supplied by locally mined silver from "Five Element"-type veins, in the 15-18th Centuries. The silver coins minted there were called "joachimsthaller", later thaller, providing name for the Austrian tolar and eventually dollar, the most recent denomination of a number of world currencies. The top-right picture from the "Kutná Hora Codex" shows the arduous conditions of Medieval silver mining. Both Jáchymov and Kutná Hora deposits, now in Czech Republic, were "world class" silver producers in the period shortly predating the rediscovery of the Americas in 1492, but the mining did not survive the competition of silver imports to Europe from

Mexico (Guanajuato Ag "giant" at bottom-right), Peru and Bolivia (Potosí Ag-Sn super-giant, bottom left, showing the Cerro Rico, a national monument endowed with over 100 Kt Ag and 1 Mt Sn). Laznicka, 2012.

Fig. 5.5. Sudbury, Ontario, Canada, the #2 Ni producer from sulfidic ores in the world. Top left shows the Canadian Shield scenery before ore discovery in the 1800s. Top right is a part of the discovery outcrop exposed in a railway cut, subsequently swallowed by the adjacent Murray Mine (bottom left) in the 1970s. On bottom right is the Sudbury ore, a sublayer breccia infilled with massive pyrrhotite, pentlandite, chalcopyrite. At bottom centre is the Big Nickel, a local monument commemorating the Canadian 5 cent coin called "nickel". Laznicka, 2012.

Fig. 5.6. Howards' Pass Zn-Pb deposit at the Yukon-NWT border, NW Canada. The ore outcrop (top left, foreground) was missed by a geological party traversing on foot because of the extremely fine-grained nature of the banded galena-sphalerite ore (two samples on the right in the middle row), almost indistinguishable from the laminated limestone host rock (top row on samples plate). The deposit was eventually identified by geochemistry and explored in the 1970s (bottom left). It is not yet mined. Laznicka, 2012; the rocks/ores samples plate is also in www.datametallogenica.com., No. 379.

Fig. 5.7. Images from three gold (super)giants. Top three pictures are from the Goldstrike (Betze-Post) deposit near the NW extremity of the Carlin Trend, Nevada. Microdisseminated gold replaces brecciated limestone (top right and #6 in cross-section), and partly also older granitic rocks (unit #2). Three centre pictures are from Muruntau, Uzbekistan, the largest Au deposit outside of Witwatersrand. The sample at center-right is a low-grade ore of quartz ribbons in biotite-altered siltstone; at center-left is the huge open pit, centre right is a cross-section showing the assay-bounded gold-quartz veins and venlet stockworks mined in bulk. Bottom left is the Grasberg open pit in Indonesian Papua, with typical ore of fracture-controlled magnetite and chalcopyrite in biotite-altered granitic rocks and diatreme breccias. Laznicka, 2012.

Fig. 5.8. Olympic Dam multi-metal super-giant deposit, South Australia. Top left shows the semi-arid scenery lacking outcrop (the mineralized bedrock is 350 m below) as it was in time of the 1975 discovery by drilling a coincident gravity and magnetic anomaly. Top right shows the Whenan Shaft. In the centre are samples of the ore: breccias of repeatedly re-brecciated and sericite, hematite altered wallrocks (predominantly ~1.6 Ga potassic granite; unit 8 in the cross-section), with disseminated Cu-sulfides, "invisible" gold, and U, REE minerals. The section below shows the thick platformic cover of clastic and carbonate rocks that completely buries the mineralized basement. Laznicka, 2012, cross-section modified after BHPB Olympic Dam, 2010.

Fig. 5.9. South African Republic has the world's greatest metal and style variety of (super)giant deposits, providing a significant share of global Au, PGE, Cr, V, Mn supplies. Laznicka, 2012.

Fig. 5.10. Deceased Giants. Giant metal deposits exhausted and closed before 2012.

Fig. 6.1. Examples of giant deposits showing the conditions and techniques that led to their discovery. Laznicka, 2013.

Fig, 6.2. Witwatersrand, South Africa. Top-right picture is the discovery site (Langlaagte alias Harrison Park) near Johannesburg with shallow workings in oxidized conglomerate "reef". The block diagram on left (courtesy of the South African Chamber of Mines) shows a set of "reefs" within the Central Rand Group that cropped-out in the Johannesburg area, from where they were followed to a considerable depth. The red horizon in the middle of the block is the Magnetic Shale marker that was geophysically followed in the 1930, eventually resulting in discovery of the deeply buried "reefs" in the West Wits goldfield (bottom right section). In this section the Central Rand clastic rocks (Units 6-9) rest on the non-productive West Rand Group, and are capped by Klipriviersberg basalts (Unit 4) and Malmani Dolomite (Unit 2). Unit 5 is the Ventersdorp Contact Reef (VCR) at base of the Ventersdorp Supergroup. Laznicka, 2012.

Fig. 6.3. Setting of metallic deposits (including the ore giants) is respect to unconsolidated and rock covers. Laznicka, 2010).

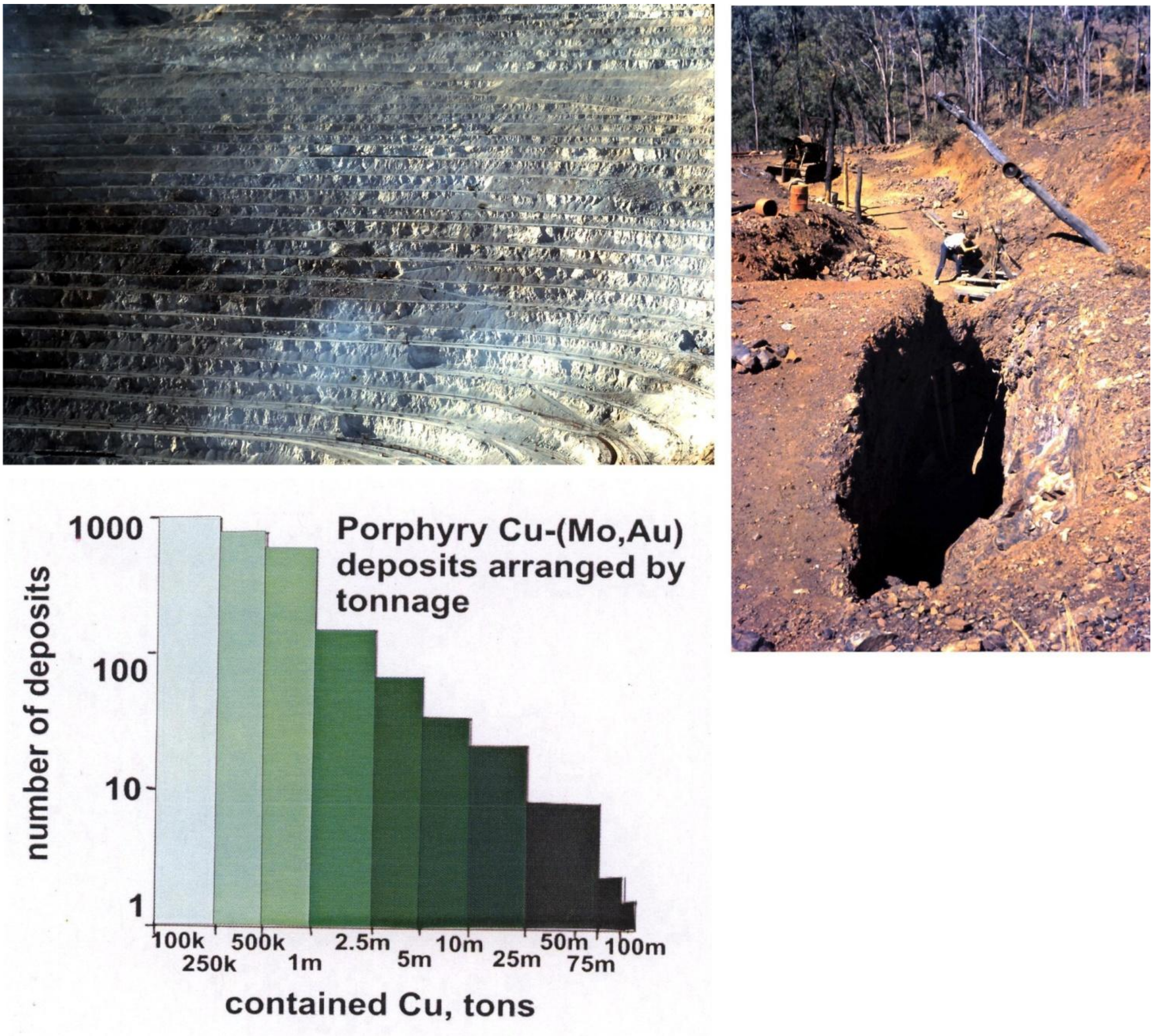
Fig. 6.4. Boddington gold deposit, Western Australia. On left is the Hedges open pit from the period when gold was being mined from residual bauxite and underlying regolith (shown as M1 in the section on right). Presently the hard rock mine produces from Au-Cu veins and stockworks (M2) in Archean greenstone metamorphic rocks and intrusions (Units 5 and 6). Unit 2 is a post-ore diabase that disrupts the orebodies. Laznicka, 2012.

Fig. 6.5. The depth of occurrence of selected significant metallic deposits under cover. Laznicka, 2010.

Fig. 7.1. Ten ore types that contain giant copper deposits. The porphyry deposits have the greatest share (59.7 %) of "giants". Laznicka, 2012.

Fig. 7.2. Approximate vertical extent of the various types of metallic deposits under the present erosional surface. This approximates the frequency of deposits anticipated at various depth levels. Laznicka, 2010.

Figure 1.1



Porphyry Cu-(Mo,Au) deposits arranged by tonnage
number of deposits
1000
100
10
1
100k
250k
500k
1m
2.5m
5m
10m
25m
50m
75m
100m
contained Cu, tons

Figure 2.1

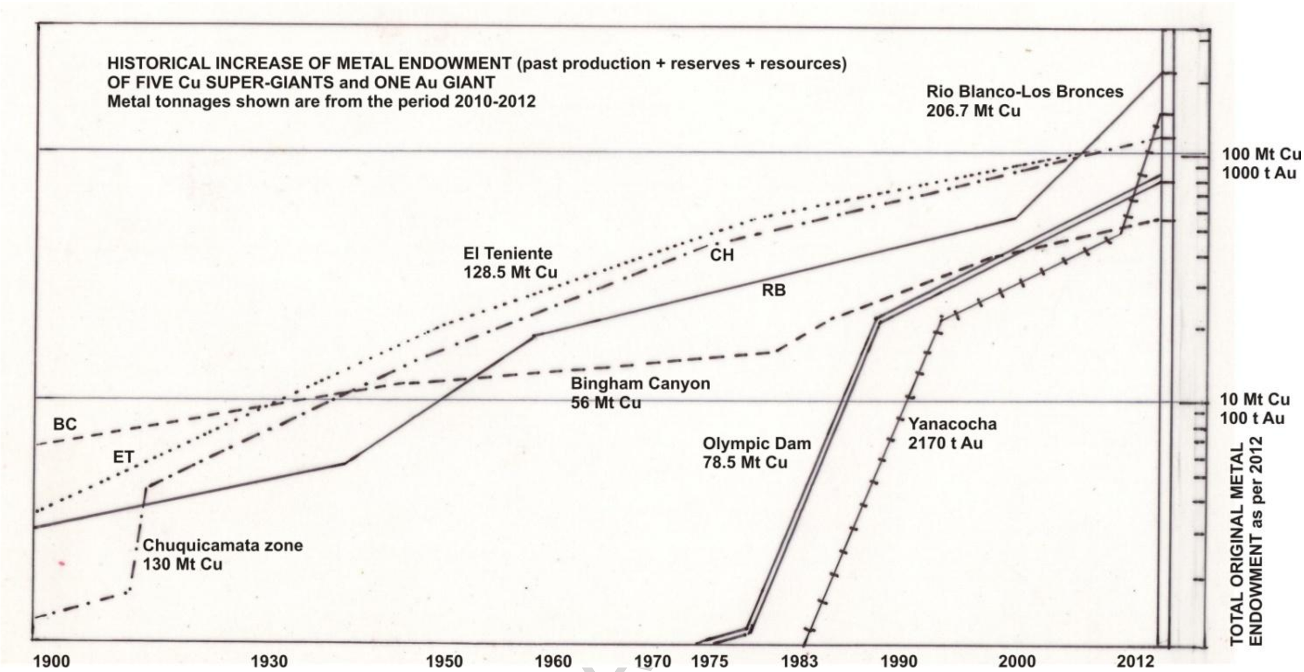
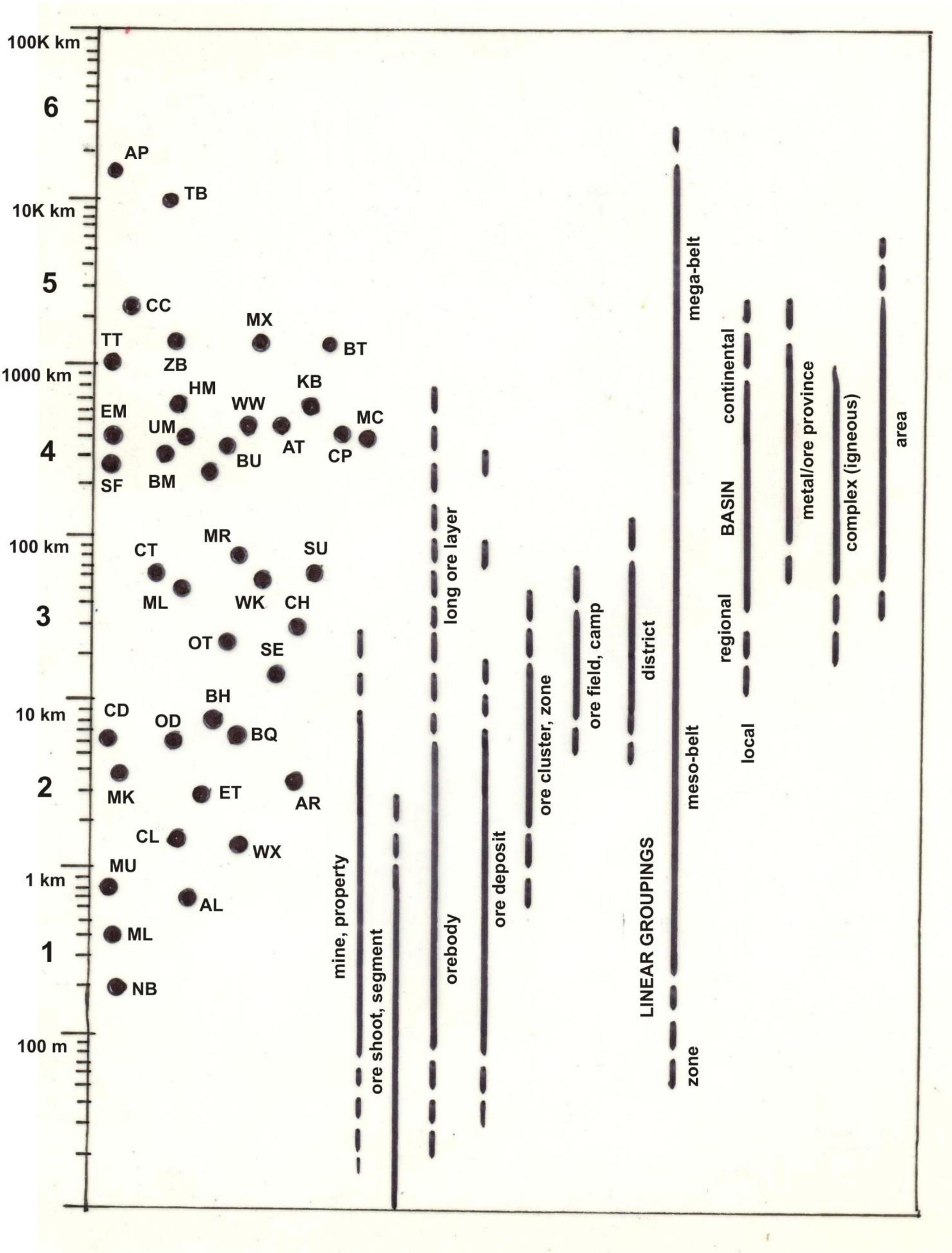

HISTORICAL INCREASE OF METAL ENDOWMENT (past production + reserves + resources)
OF FIVE Cu SUPER-GIANTS and ONE Au GIANT
Metal tonnages shown are from the period 2010-2012
Rio Blanco-Los Bronces
206.7 Mt Cu
100 Mt Cu
1000 t Au
El Teniente
128.5 Mt Cu
CH
RB
Bingham Canyon
56 Mt Cu
10 Mt Cu
100 t Au
BC
ET
Olympic Dam
78.5 Mt Cu
Yanacocha
2170 t Au
Chuquicamata zone
130 Mt Cu
TOTAL ORIGINAL METAL ENDOWMENT as per 2012
1900
1930
1950
1960
1970
1975
1983
1990
2000
2012

Figure 2.2



100K km
6
AP
TB
10K km
5
CC
MX
TT
ZB
BT
1000 km
HM
KB
EM
WW
MC
UM
AT
4
BU
CP
SF
BM
100 km
CT
MR
SU
ML
WK
CH
3
OT
SE
BH
10 km
CD
OD
BQ
2
MK
ET
AR
CL
WX
MU
1 km
AL
ML
1
NB
100 m
mine, property
ore shoot, segment
long ore layer
orebody
ore deposit
ore cluster, zone
ore field, camp
district
LINEAR GROUPINGS
mega-belt
meso-belt
zone
continental
BASIN
regional
local
metal/ore province
complex (igneous)
area

Figure 2.3

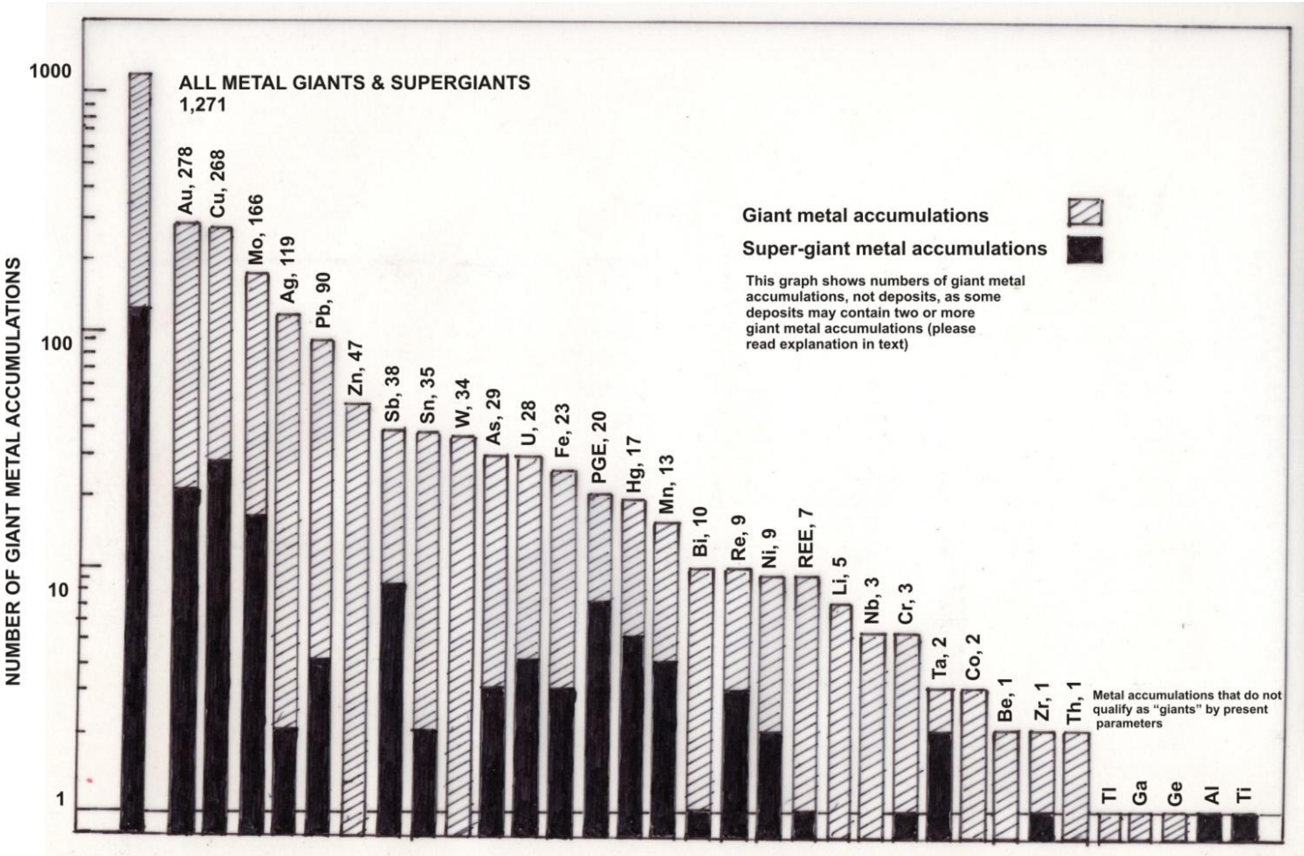

1000
100
10
1
NUMBER OF GIANT METAL ACCUMULATIONS
ALL METAL GIANTS & SUPERGIANTS
1,271
Au, 278
Cu, 268
Mo, 166
Ag, 119
Pb, 90
Zn, 47
Sb, 38
Sn, 35
W, 34
As, 29
U, 28
Fe, 23
PGE, 20
Hg, 17
Mn, 13
Bi, 10
Re, 9
Ni, 9
REE, 7
Li, 5
Nb, 3
Cr, 3
Ta, 2
Co, 2
Be, 1
Zr, 1
Th, 1
Tl
Ga
Ge
Al
Ti
Giant metal accumulations
Super-giant metal accumulations
This graph shows numbers of giant metal accumulations, not deposits, as some deposits may contain two or more giant metal accumulations (please read explanation in text)
Metal accumulations that do not qualify as "giants" by present parameters

Figure 3.1

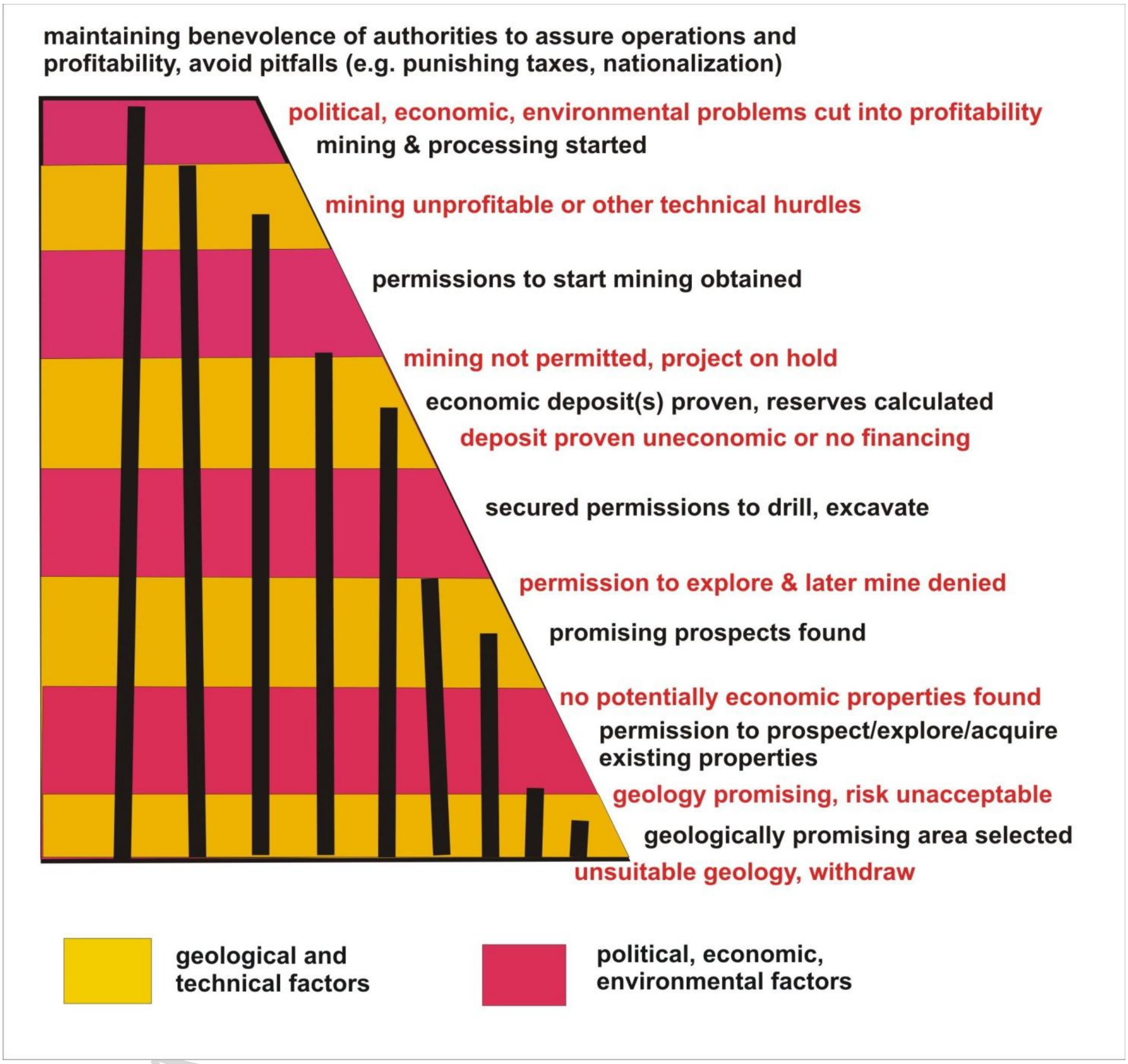

maintaining benevolence of authorities to assure operations and
profitability, avoid pitfalls (e.g. punishing taxes, nationalization)
political, economic, environmental problems cut into profitability
mining & processing started
mining unprofitable or other technical hurdles
permissions to start mining obtained
mining not permitted, project on hold
economic deposit(s) proven, reserves calculated
deposit proven uneconomic or no financing
secured permissions to drill, excavate
permission to explore & later mine denied
promising prospects found
no potentially economic properties found
permission to prospect/explore/acquire
existing properties
geology promising, risk unacceptable
geologically promising area selected
unsuitable geology, withdraw
geological and
technical factors
political, economic,
environmental factors

Figure 3.2

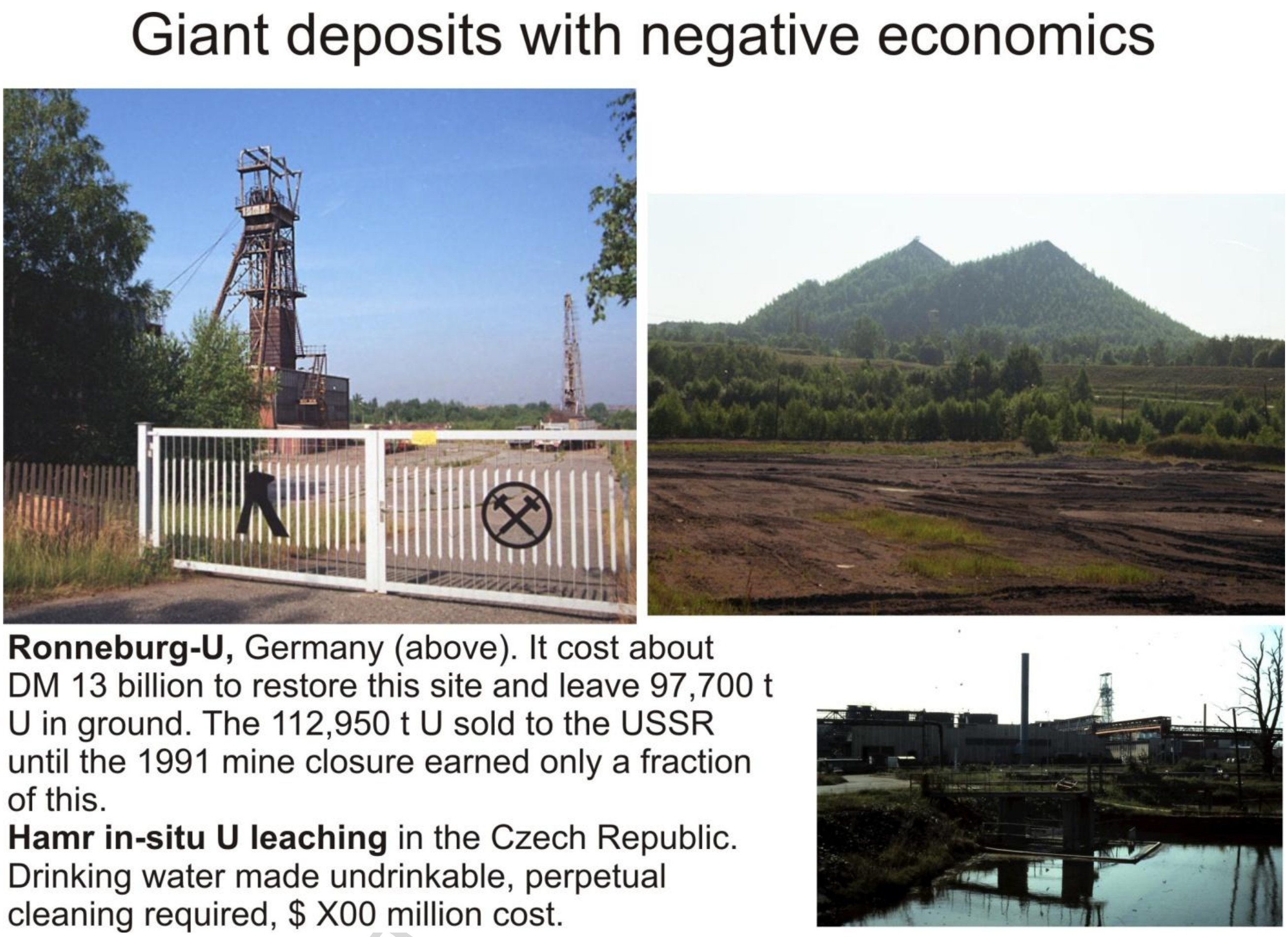

Giant deposits with negative economics
Ronneburg-U, Germany (above). It cost about DM 13 billion to restore this site and leave 97,700 t U in ground. The 112,950 t U sold to the USSR until the 1991 mine closure earned only a fraction of this.
Hamr in-situ U leaching in the Czech Republic. Drinking water made undrinkable, perpetual cleaning required, $ X00 million cost.

Figure 3.3

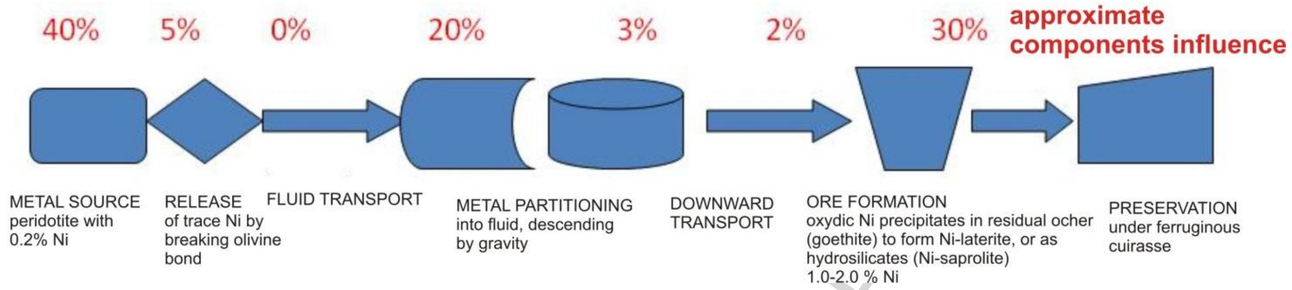

40%
5%
0%
20%
3%
2%
30%
approximate components influence
METAL SOURCE peridotite with 0.2% Ni
RELEASE of trace Ni by breaking olivine bond
FLUID TRANSPORT
METAL PARTITIONING into fluid, descending by gravity
DOWNWARD TRANSPORT
ORE FORMATION oxydic Ni precipitates in residual ocher (goethite) to form Ni-laterite, or as hydrosilicates (Ni-saprolite) 1.0-2.0 % Ni
PRESERVATION under ferruginous cuirasse

Figure 4.1

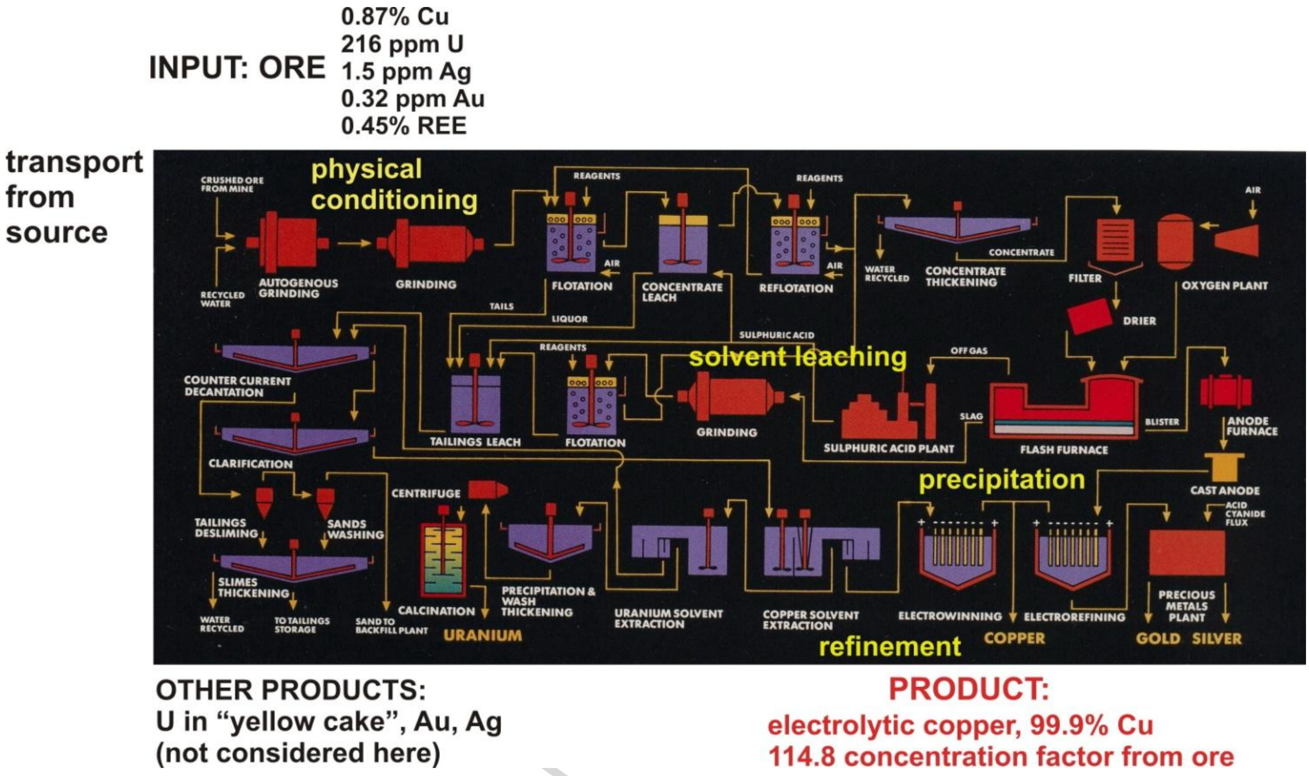
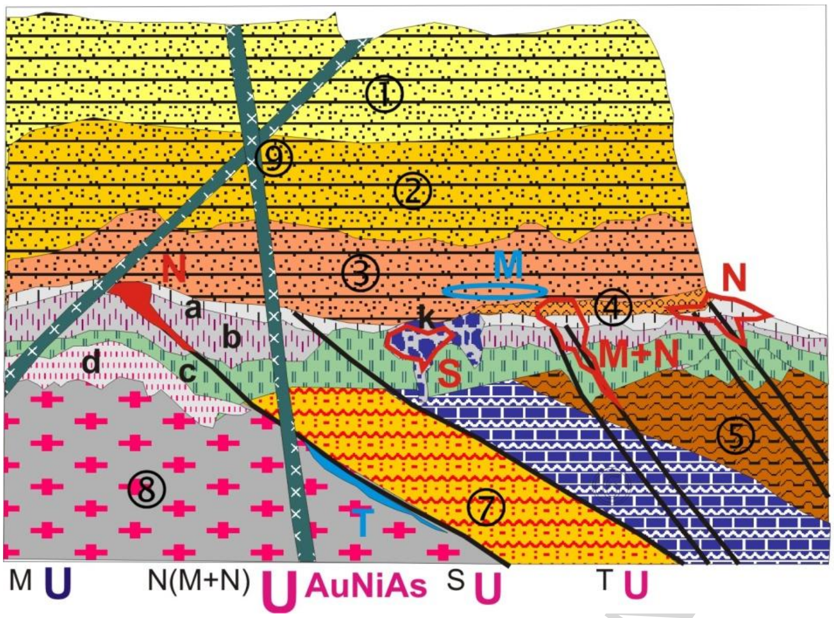
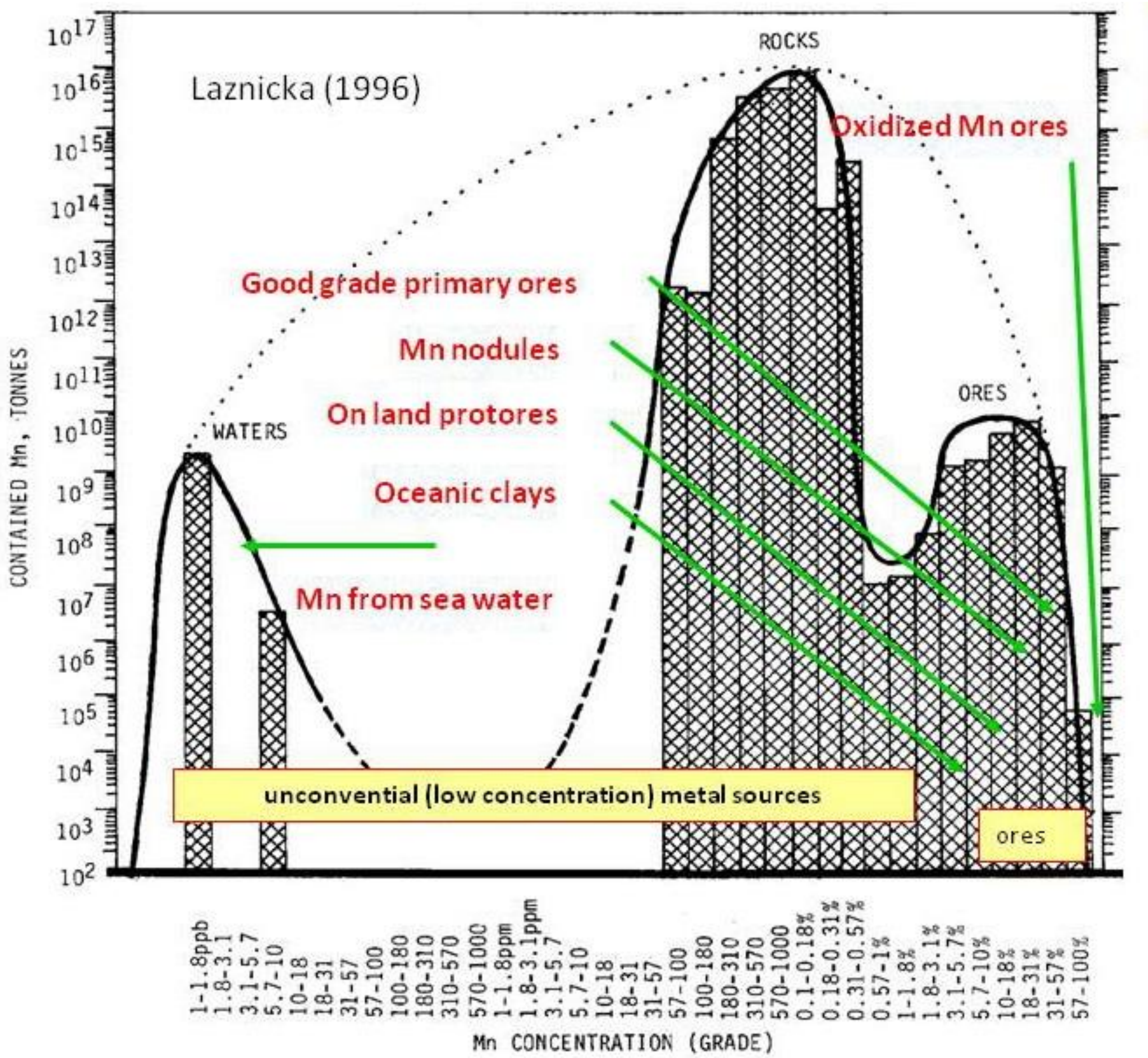

INPUT: ORE
0.87% Cu
216 ppm U
1.5 ppm Ag
0.32 ppm Au
0.45% REE
transport from source
physical conditioning
solvent leaching
precipitation
refinement
CRUSHED ORE FROM MINE
RECYCLED WATER
AUTOGENOUS GRINDING
GRINDING
REAGENTS
FLOTATION
AIR
CONCENTRATE LEACH
REFLOTATION
WATER RECYCLED
CONCENTRATE THICKENING
CONCENTRATE
FILTER
DRIER
OXYGEN PLANT
TAILS
LIQUOR
SULPHURIC ACID
OFF GAS
COUNTER CURRENT DECANTATION
TAILINGS LEACH
SULPHURIC ACID PLANT
SLAG
FLASH FURNACE
BLISTER
ANODE FURNACE
CLARIFICATION
CENTRIFUGE
CAST ANODE
ACID CYANIDE FLUX
TAILINGS DESLIMING
SANDS WASHING
SLIMES THICKENING
WATER RECYCLED
TO TAILINGS STORAGE
SAND TO BACKFILL PLANT
CALCINATION
URANIUM
PRECIPITATION & WASH THICKENING
URANIUM SOLVENT EXTRACTION
COPPER SOLVENT EXTRACTION
ELECTROWINNING
ELECTROREFINING
COPPER
PRECIOUS METALS PLANT
GOLD
SILVER
OTHER PRODUCTS:
U in “yellow cake”, Au, Ag
(not considered here)
PRODUCT:
electrolytic copper, 99.9% Cu
114.8 concentration factor from ore

Figure 4.2



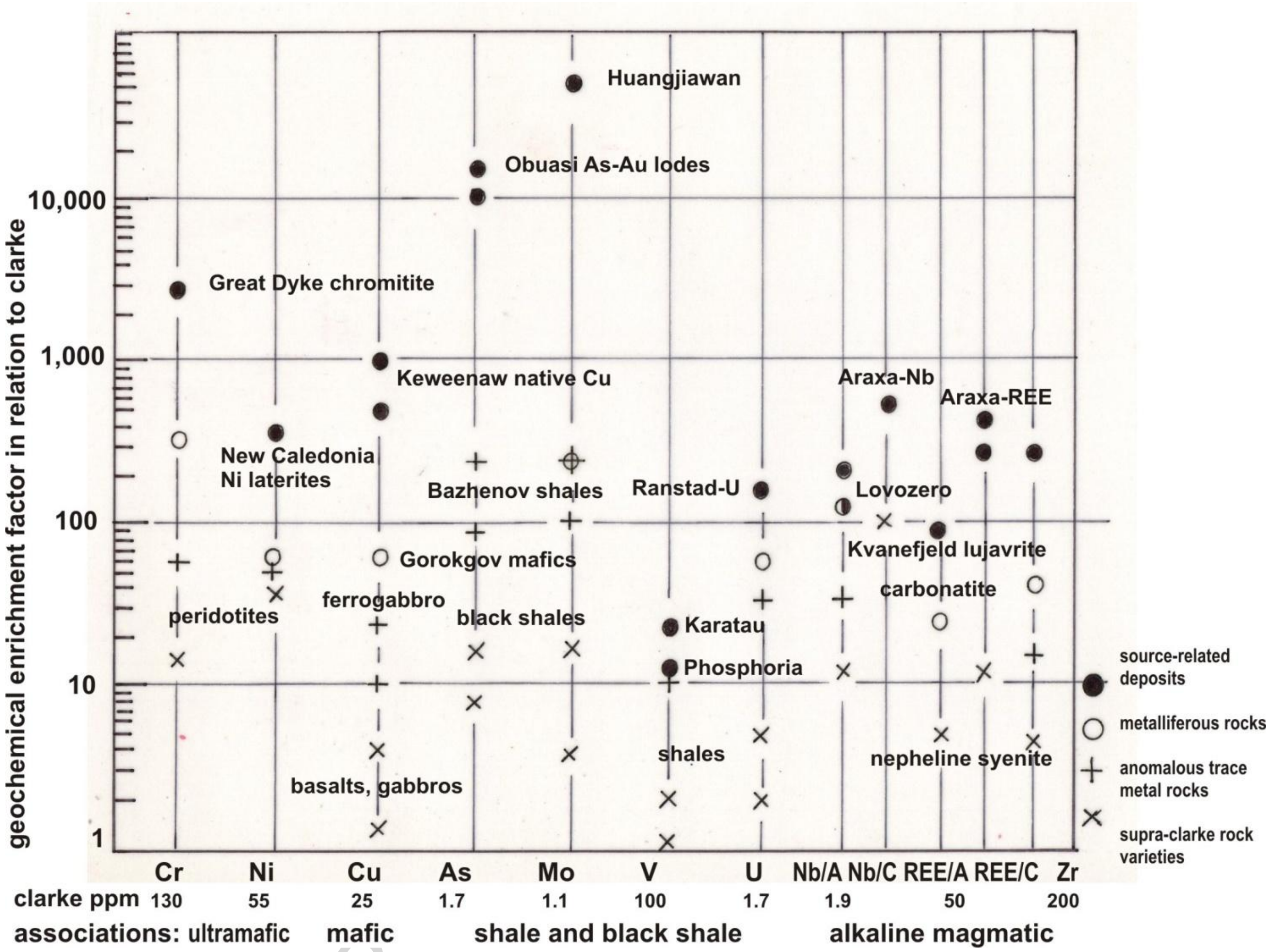
M. U, sandstone infiltrations above unconformity
N. U(Au,Ni,As) "unconformity-U" under unconformity in tectonized crystalline basement
M+N. M & N combined
S. U in collophanite (apatite) in paleokarsted marbles
T. U disseminated in albitized faults

Figure 4.3



Laznicka (1996)
ROCKS
WATERS
ORES
Oxidized Mn ores
Good grade primary ores
Mn nodules
On land protores
Oceanic clays
Mn from sea water
unconvential (low concentration) metal sources
ores
CONTAINED Mn, TONNES
Mn CONCENTRATION (GRADE)

Figure 4.4



geochemical enrichment factor in relation to clarke
10,000
1,000
100
10
1
Huangjiawan
Obuasi As-Au lodes
Great Dyke chromitite
Keweenaw native Cu
New Caledonia
Ni laterites
Bazhenov shales
Ranstad-U
Araxa-Nb
Araxa-REE
Lovozero
Kvanefjeld lujavrite
carbonatite
Gorokgov mafics
ferrogabbro
peridotites
black shales
Karatau
Phosphoria
shales
nepheline syenite
basalts, gabbros
source-related deposits
metalliferous rocks
anomalous trace metal rocks
supra-clarke rock varieties
Cr Ni Cu As Mo V U Nb/A Nb/C REE/A REE/C Zr
clarke ppm 130 55 25 1.7 1.1 100 1.7 1.9 50 200
associations: ultramafic mafic shale and black shale alkaline magmatic

Figure 4.5

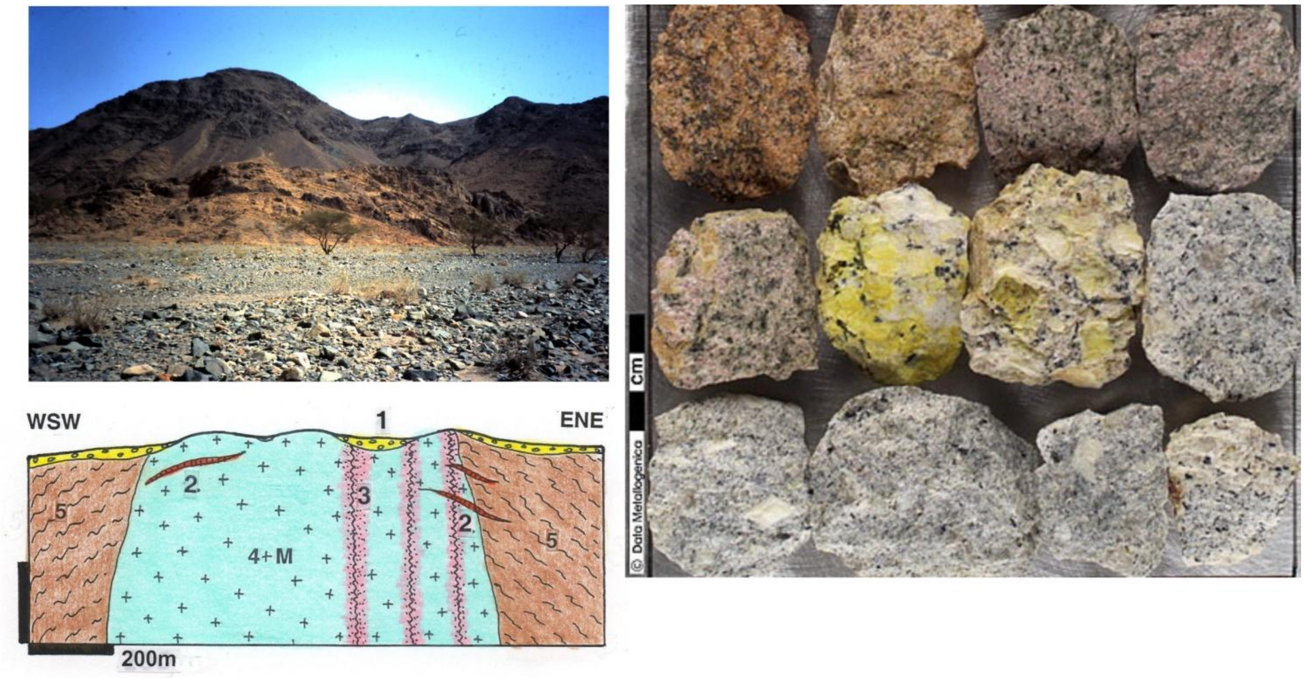


Figure 4.6

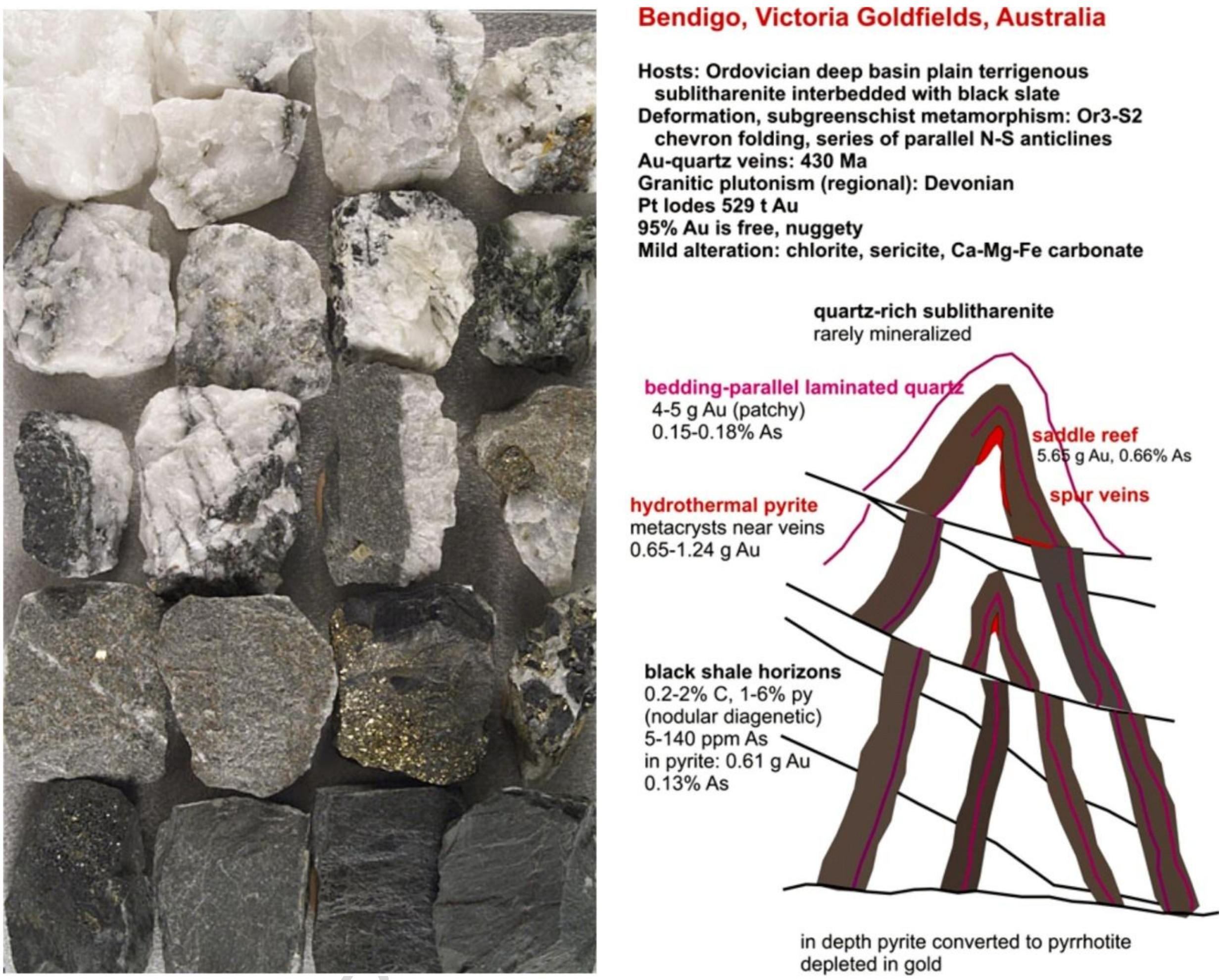
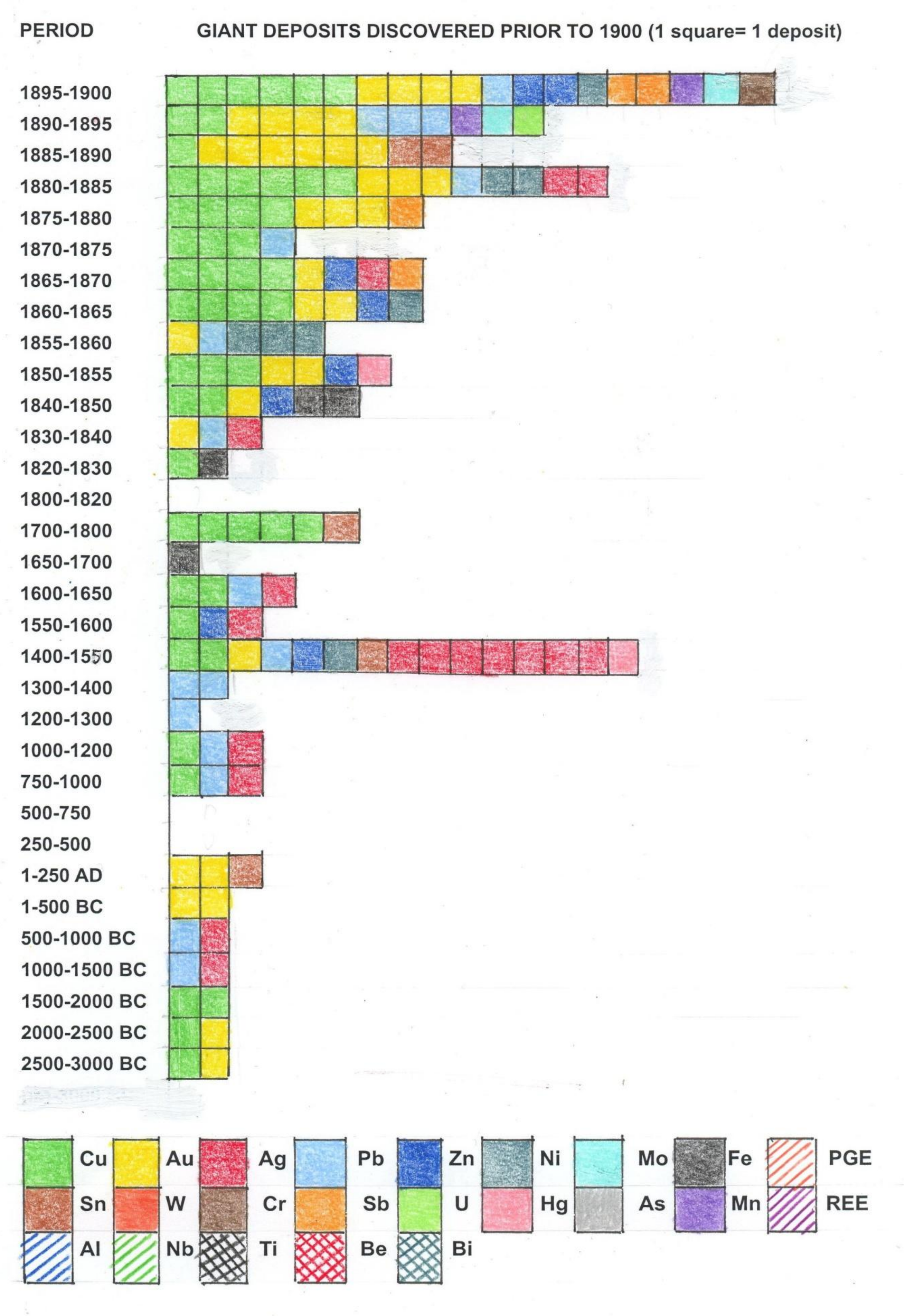

Bendigo, Victoria Goldfields, Australia
Hosts: Ordovician deep basin plain terrigenous sublitharenite interbedded with black slate
Deformation, subgreenschist metamorphism: Or3-S2 chevron folding, series of parallel N-S anticlines
Au-quartz veins: 430 Ma
Granitic plutonism (regional): Devonian
Pt lodes 529 t Au
95% Au is free, nuggety
Mild alteration: chlorite, sericite, Ca-Mg-Fe carbonate
quartz-rich sublitharenite
rarely mineralized
bedding-parallel laminated quartz
4-5 g Au (patchy)
0.15-0.18% As
saddle reef
5.65 g Au, 0.66% As
spur veins
hydrothermal pyrite
metacrysts near veins
0.65-1.24 g Au
black shale horizons
0.2-2% C, 1-6% py
(nodular diagenetic)
5-140 ppm As
in pyrite: 0.61 g Au
0.13% As
in depth pyrite converted to pyrrhotite
depleted in gold

Figure 4.7



PERIOD
GIANT DEPOSITS DISCOVERED PRIOR TO 1900 (1 square= 1 deposit)
1895-1900
1890-1895
1885-1890
1880-1885
1875-1880
1870-1875
1865-1870
1860-1865
1855-1860
1850-1855
1840-1850
1830-1840
1820-1830
1800-1820
1700-1800
1650-1700
1600-1650
1550-1600
1400-1550
1300-1400
1200-1300
1000-1200
750-1000
500-750
250-500
1-250 AD
1-500 BC
500-1000 BC
1000-1500 BC
1500-2000 BC
2000-2500 BC
2500-3000 BC
Cu
Au
Ag
Pb
Zn
Ni
Mo
Fe
PGE
Sn
W
Cr
Sb
U
Hg
As
Mn
REE
Al
Nb
Ti
Be
Bi

Figure 5.1

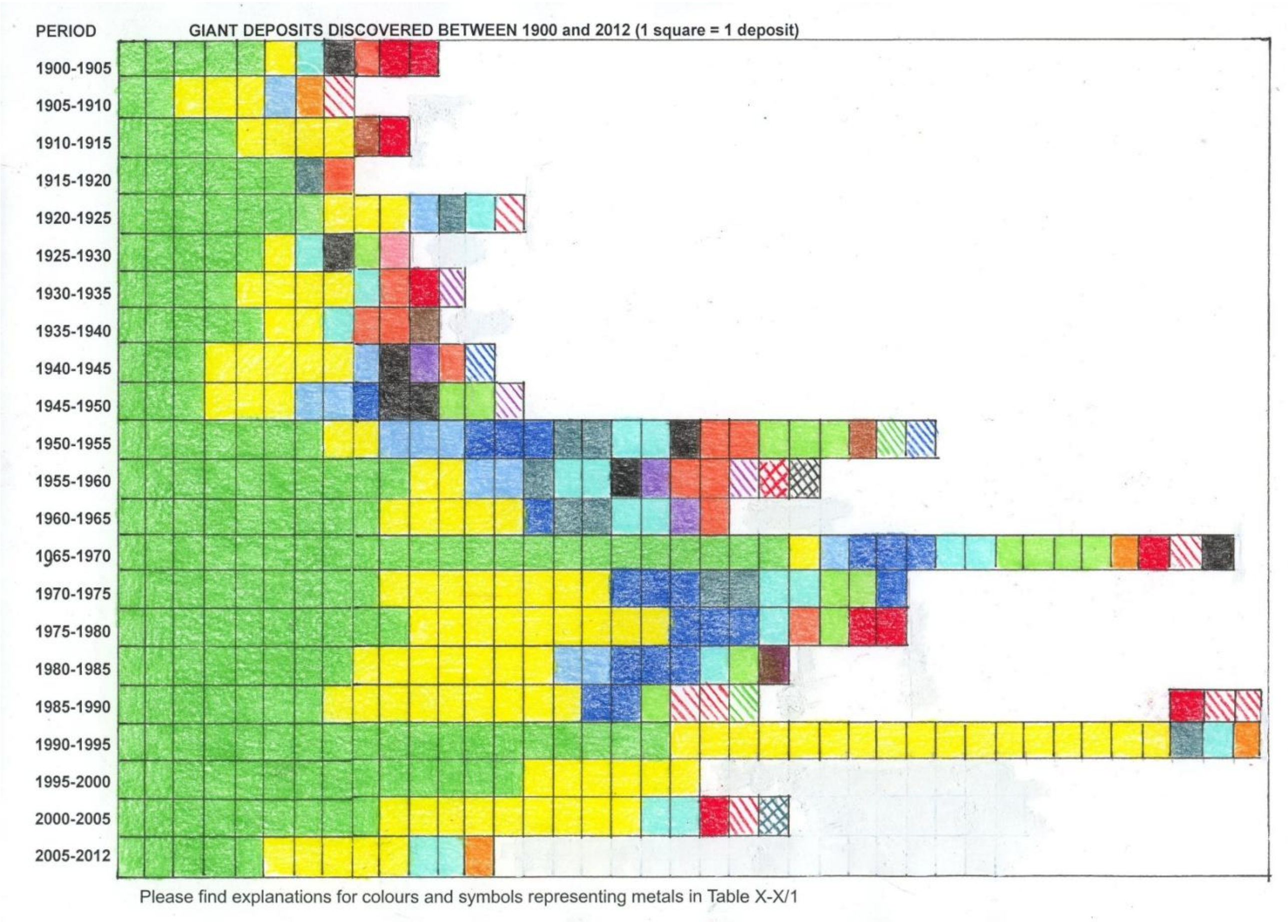

PERIOD
GIANT DEPOSITS DISCOVERED BETWEEN 1900 and 2012 (1 square = 1 deposit)
1900-1905
1905-1910
1910-1915
1915-1920
1920-1925
1925-1930
1930-1935
1935-1940
1940-1945
1945-1950
1950-1955
1955-1960
1960-1965
1965-1970
1970-1975
1975-1980
1980-1985
1985-1990
1990-1995
1995-2000
2000-2005
2005-2012
Please find explanations for colours and symbols representing metals in Table X-X/1

Figure 5.2

Figure 5.3

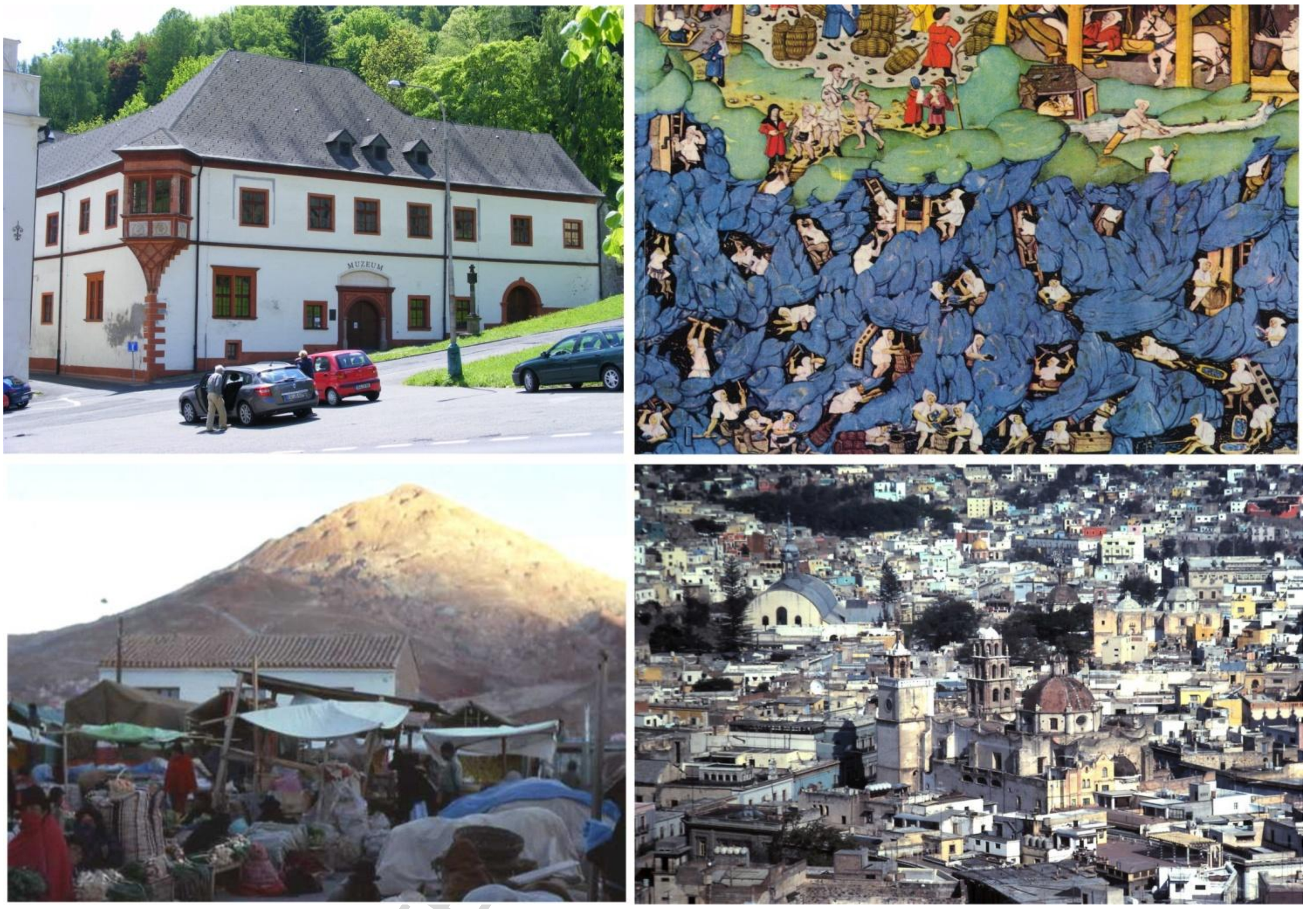


Figure 5.4

Figure 5.5

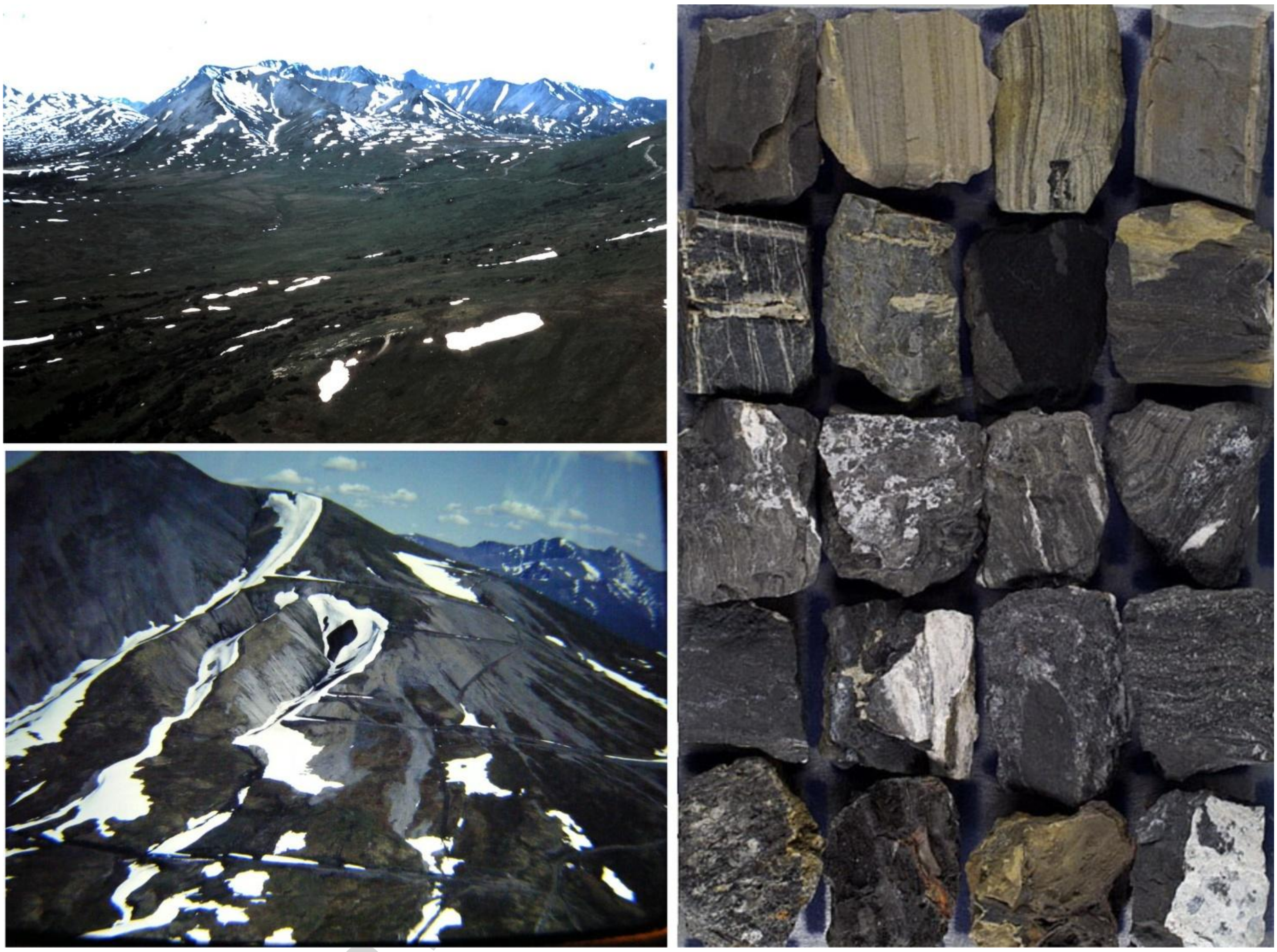


Figure 5.6

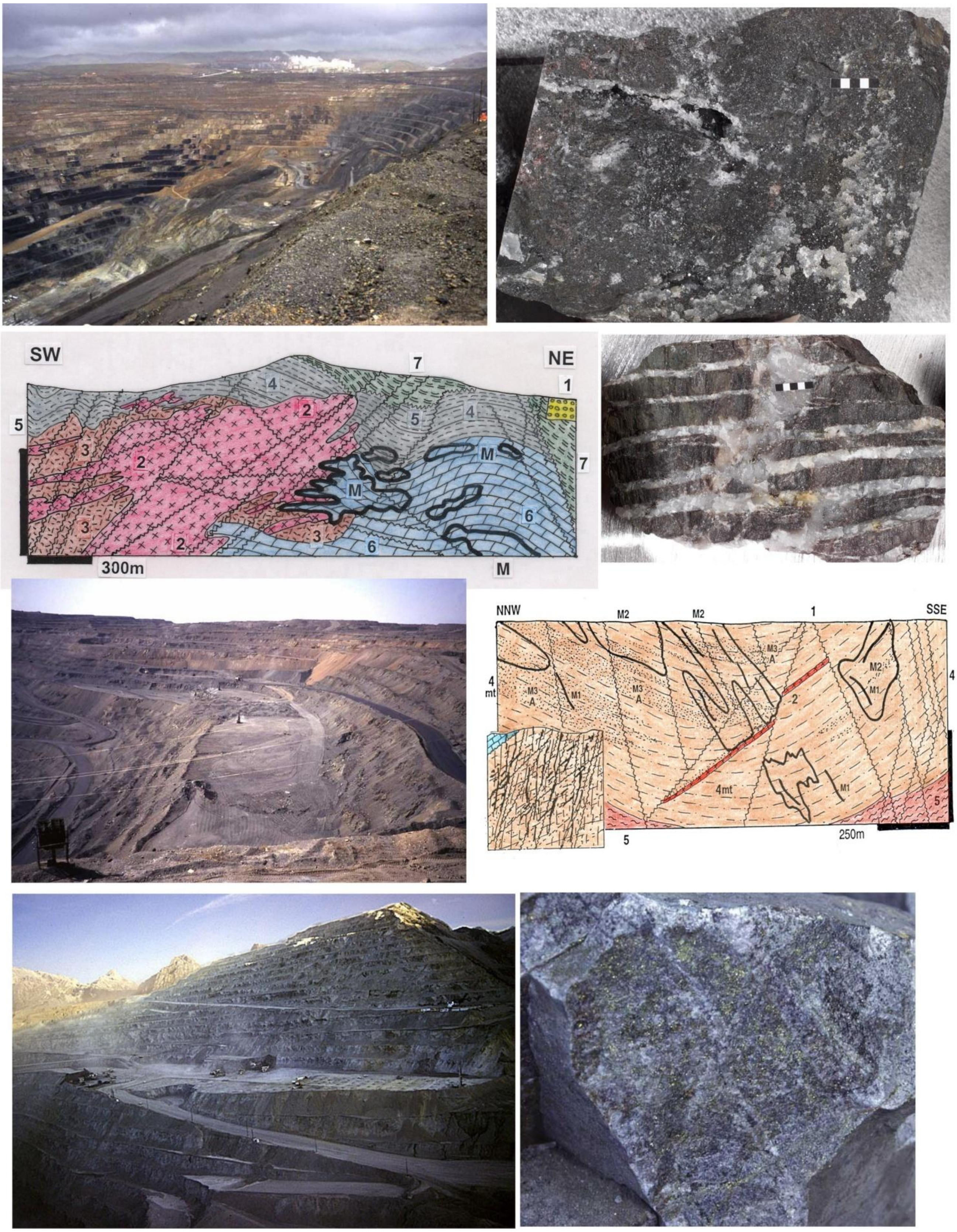


Figure 5.7

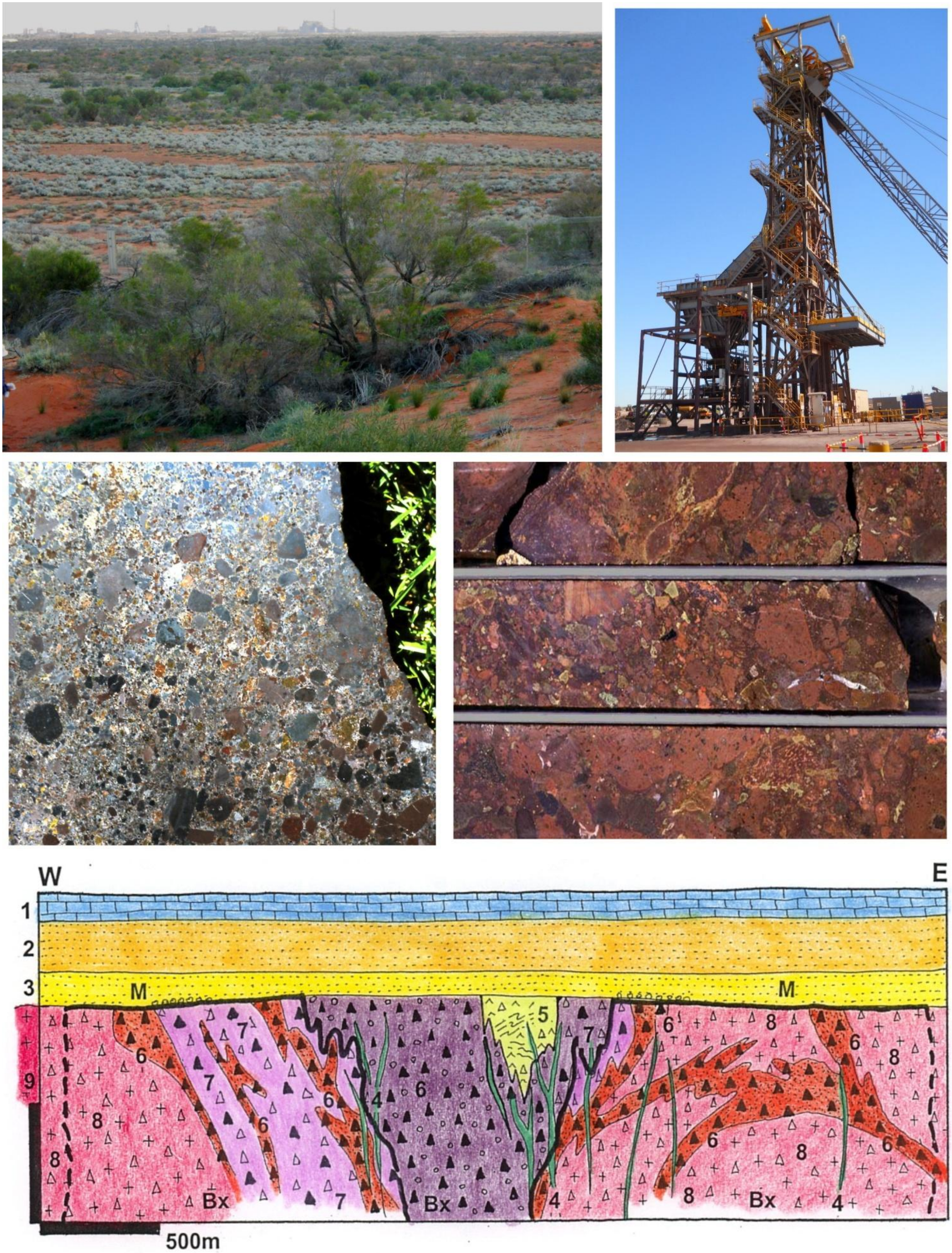


Figure 5.8

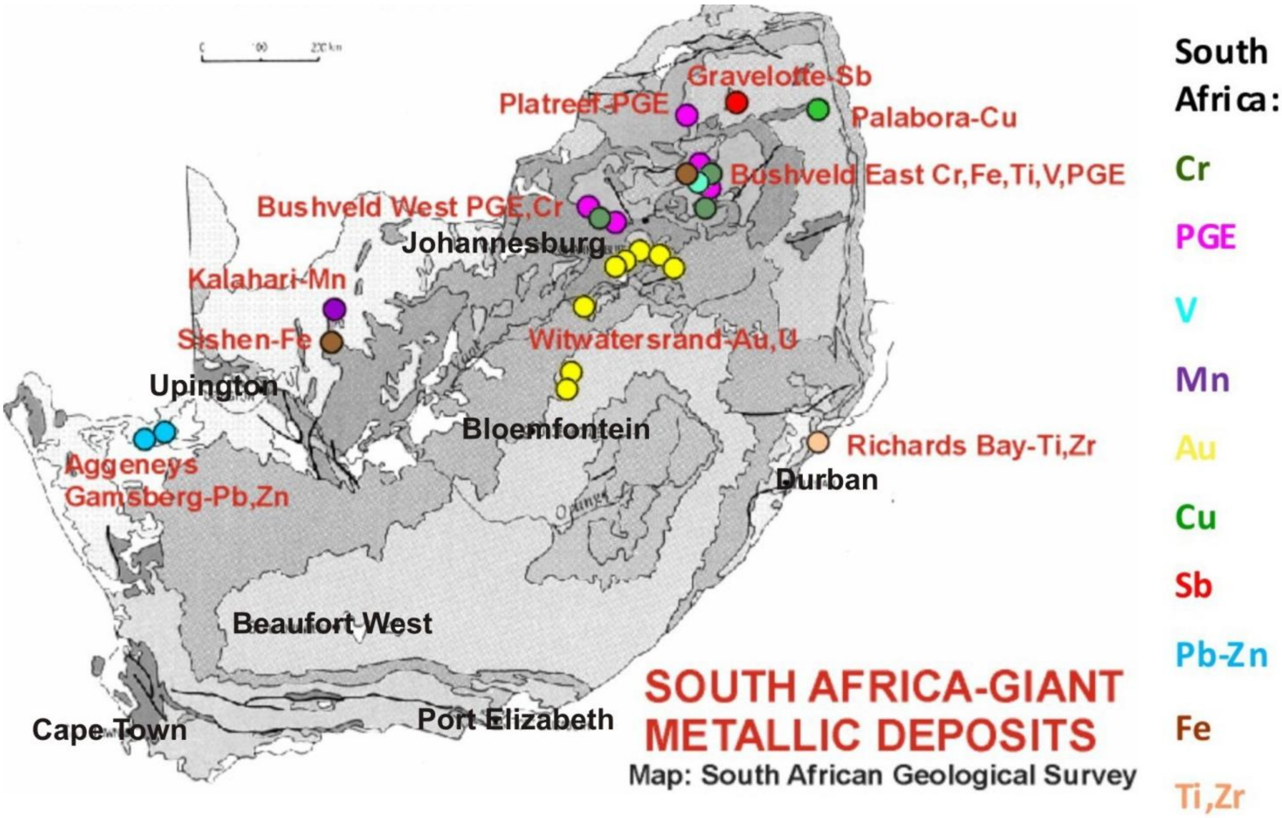

Gravelotte-Sb
Platreef-PGE
Palabora-Cu
Bushveld East Cr,Fe,Ti,V,PGE
Bushveld West PGE,Cr
Johannesburg
Kalahari-Mn
Sishen-Fe
Witwatersrand-Au,U
Upington
Bloemfontein
Richards Bay-Ti,Zr
Durban
Aggeneys
Gamsberg-Pb,Zn
Beaufort West
Cape Town
Port Elizabeth
SOUTH AFRICA-GIANT
METALLIC DEPOSITS
Map: South African Geological Survey
South
Africa:
Cr
PGE
V
Mn
Au
Cu
Sb
Pb-Zn
Fe
Ti,Zr

Figure 5.9

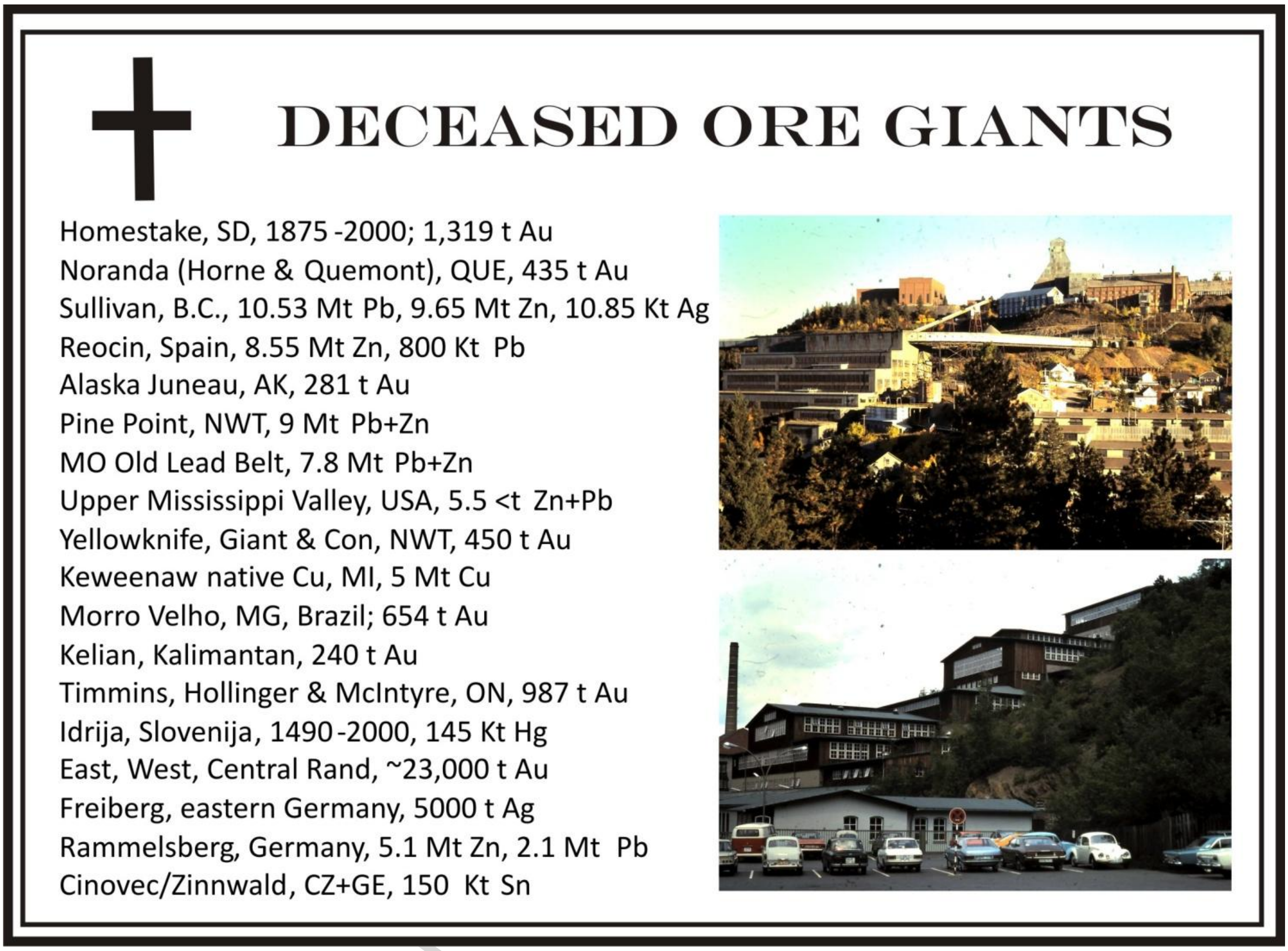

DECEASED ORE GIANTS
Homestake, SD, 1875 -2000; 1,319 t Au
Noranda (Horne & Quemont), QUE, 435 t Au
Sullivan, B.C., 10.53 Mt Pb, 9.65 Mt Zn, 10.85 Kt Ag
Reocin, Spain, 8.55 Mt Zn, 800 Kt Pb
Alaska Juneau, AK, 281 t Au
Pine Point, NWT, 9 Mt Pb+Zn
MO Old Lead Belt, 7.8 Mt Pb+Zn
Upper Mississippi Valley, USA, 5.5 <t Zn+Pb
Yellowknife, Giant & Con, NWT, 450 t Au
Keweenaw native Cu, MI, 5 Mt Cu
Morro Velho, MG, Brazil; 654 t Au
Kelian, Kalimantan, 240 t Au
Timmins, Hollinger & McIntyre, ON, 987 t Au
Idrija, Slovenija, 1490-2000, 145 Kt Hg
East, West, Central Rand, ~23,000 t Au
Freiberg, eastern Germany, 5000 t Ag
Rammelsberg, Germany, 5.1 Mt Zn, 2.1 Mt Pb
Cinovec/Zinnwald, CZ+GE, 150 Kt Sn

Figure 5.10

metal	deposit	year	logistics	maps	Government	info support	exploration model	discoverer	setting	deposit	prospecting	tracing float	panning	geochemistry	imagery	radiometry	gravity	magnetics	electrical & EM	in-hole geophysics	chip drilling	core drilling	trenching	mining (exploration)	duration	complexity
Ag,Pb	Lavrion, GR	>700 BC	F					L	G	E	&												&	&	1	1
Ag,Sn	Potosi, BO	1545	F					L	B	E	&												X	&	1	1
Cu	El Teniente, CL	1706	F					L	G	E	&												X	&	P	1
Au	Sierra Nevada Fh.	1886	F					P	G	E	&	&	&										&	&	1	1
Mo	Climax, USCO	1879	F	o	o			P	B	E	&												X	X	P	1
Au	Central Rand, SA	1882	F	o	o			P	M	E	&	X	&										X	&	1	1
Au	Kalgoorlie, AUWA	1894	F	o	o	o	o	P	M	E	&	&	&										X	&	1	1
Au	Klondike, CNYT	1896	F	o	o	o	o	P	M	E	&	&	&										X	&	1	1
Cu	Bingham Canyon	1904	F	T	o	o	o	P	B	S	X	o	o					o			o	o	o	&	2	3
Cu	Nchanga, ZA	1923	F	o	o		÷	P	B	E	&			o							o		X	&	2	3
Au	West Wits, SA	1934	A	T	+	+	X	C	B	D							+	&	o			&		X	3	3
Au	Welkom, SA	1939	A	T	+	+	&	C	B	D							&	&	o	o		&		X	3	3
U	Grants, USNM	1950	H	G	+	+	X	P	M	S	X			X	o	&	o		o	X	+	X	X	X	2	2
U	Rössing, NM	1955	A	T	+	o	+	P	M	E	&	o	o	X	o	&				o	o	X	X	X	P	3
Zn,Pb	Red Dog, USAK	1955	H	G	X	+	+	G	G	E	X	o	o	&	X		o	o	X	X	X	&	X	X	P	1
Au	Muruntau, UZ	1958	A	G	&	+	o	G	M	E	+			o	o	&			o	X	o	&	&	X	3	1
W	Felbertal, AS	1960s	F	G	X	X	&	A	G	E	&	o		o								X	o	X	3	1
Au	Carlin 1, USNV	1962	A	G	+	X	X	C	M	E	X	o	o	&					o	X	X	X	o	X	2	2

Figure 6.1a

metal	deposit	year	logistics	maps	Government	info support	exploration model	discoverer	setting	deposit	prospecting	tracing float	panning	geochemistry	imagery	radiometry	gravity	magnetics	electrical & EM	in-hole geophysics	chip drilling	core drilling	trenching	mining (exploration)	duration	complexity
Zn,Cu	Kidd Creek, CNON	1962	A	G	+	X	X	C	B	S	+	o		■			X	X	■	X	o	■	X	X	2	2
Ni	Kambalda, AUWA	1965	A	G	+	X	X	C	B	S	■	o	o	■				o	X	X	o	■	X	X	2	2
Zn	Elmwood, USTN	1967	A	G	+	X	X	C	G	D							■			X		■		o	3	1
Cu	Kalamazoo, USAZ	1968	A	G	+	X	■	C	B	D							o	o		X		■		■	1	5
Zn,Pb	Howards Pass, CN	1972	H	G	+	X	+	C	G	E	■			■	o				X	X	o	■	X		P	1
Cu,Au	Olympic Dam, AU	1975	A	S	■	■	■	C	M	D						o	■	■	+	X		■		o	P	1
Cu	Escondida, CL	1977	F	G	+	X	&	C	G	S	■			■	o			o	X	X	■	X	X	o	P	2
Cu,Sn	Corvo Neves, PT	1977	A	G	+	X	■	C	M	D				o			■	■	X	X		■		■	P	4
Au	Boddington, AUWA	1980	A	G	X	+	o	C	M	S	+	o	+	■				o	X	+	■	■	X	X	2	5
Au	Hishikari, JP	1980	A	G	+	X	X	G	B	S	+	o	+	■			o	o	+	X	o	&	X	X	2	2
Au	Ladolam, PNG	1982	B	G	X	+	+	C	G	E	■	+	o	o	o				+	+	&	■	X	X	P	1
Au,Ag	Yanacocha, PE	1983	F	G	+	+	+	C	G	S	■	X	+	■	o				+	X	■	■	X	■	3	2
Au	Goldstrike, USNV	1986	A	S	X	■	■	C	B	D				X			o	o	X	X	X	■		■	2	5
Cu,Au	Grasberg, ID	1988	A	G	X	X	X	C	B	S	o			X	o			o	X	X	X	■		X	2	5
Cu,Au	Pebble, USAK	1989	H	G	+	+	X	C	M	S	X	X	X	■	+			o	X	X	■	X	X	X	P	2
Cu,Au	Batu Hijau, ID	1990	F	G	X	+	X	C	G	S	X	o	+	■	+				+	+	■	■	o	X	3	1
Cu,Au	Cadia 2, AUNW	1994	A	S	X	■	■	C	B	D	o			X			o	o	X	X		&		■	P	5
Cu	Resolution, USAZ	1995	A	G	X	X	X	C	B	D				o			o	o	X	X		■		■	P	5
Cu,Au	Oyu Tolgoi, MO	1996	F	G	■	+	X	G	G	S	■	o	o	■	X			X	■	X	■	■	X	o	3	3
Cu	Carrapateena, AU	2006	A	S	X	■	■	C	B	D						o	■	■	X	X		■		o	P	1

Figure 6.1b

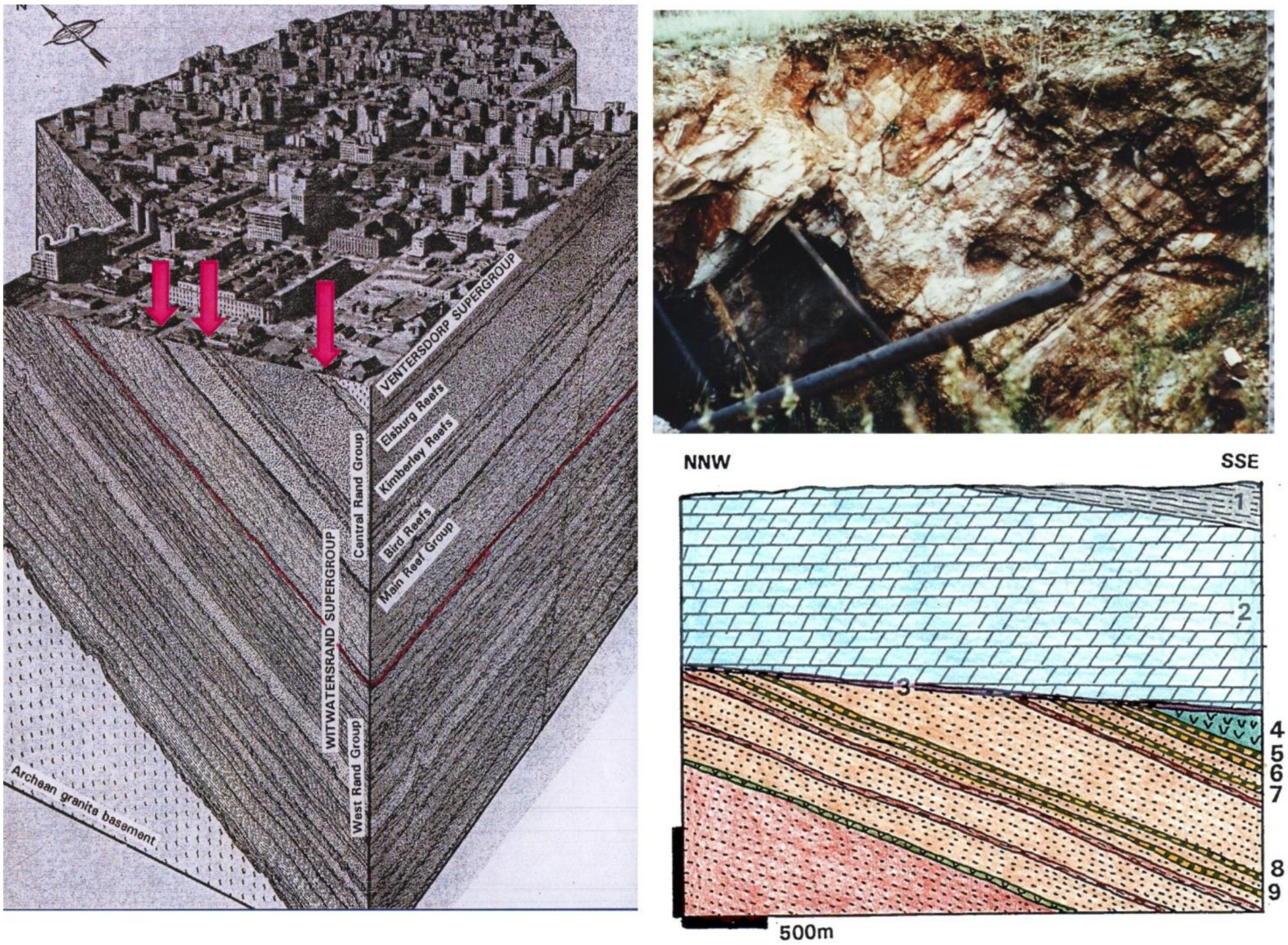

N
VENTERSDORP SUPERGROUP
Elsburg Reefs
Kimberley Reefs
Central Rand Group
Bird Reefs
Main Reef Group
WITWATERSRAND SUPERGROUP
West Rand Group
Archean granite basement
NNW
SSE
1
2
3
4
5
6
7
8
9
500m

Figure 6.2

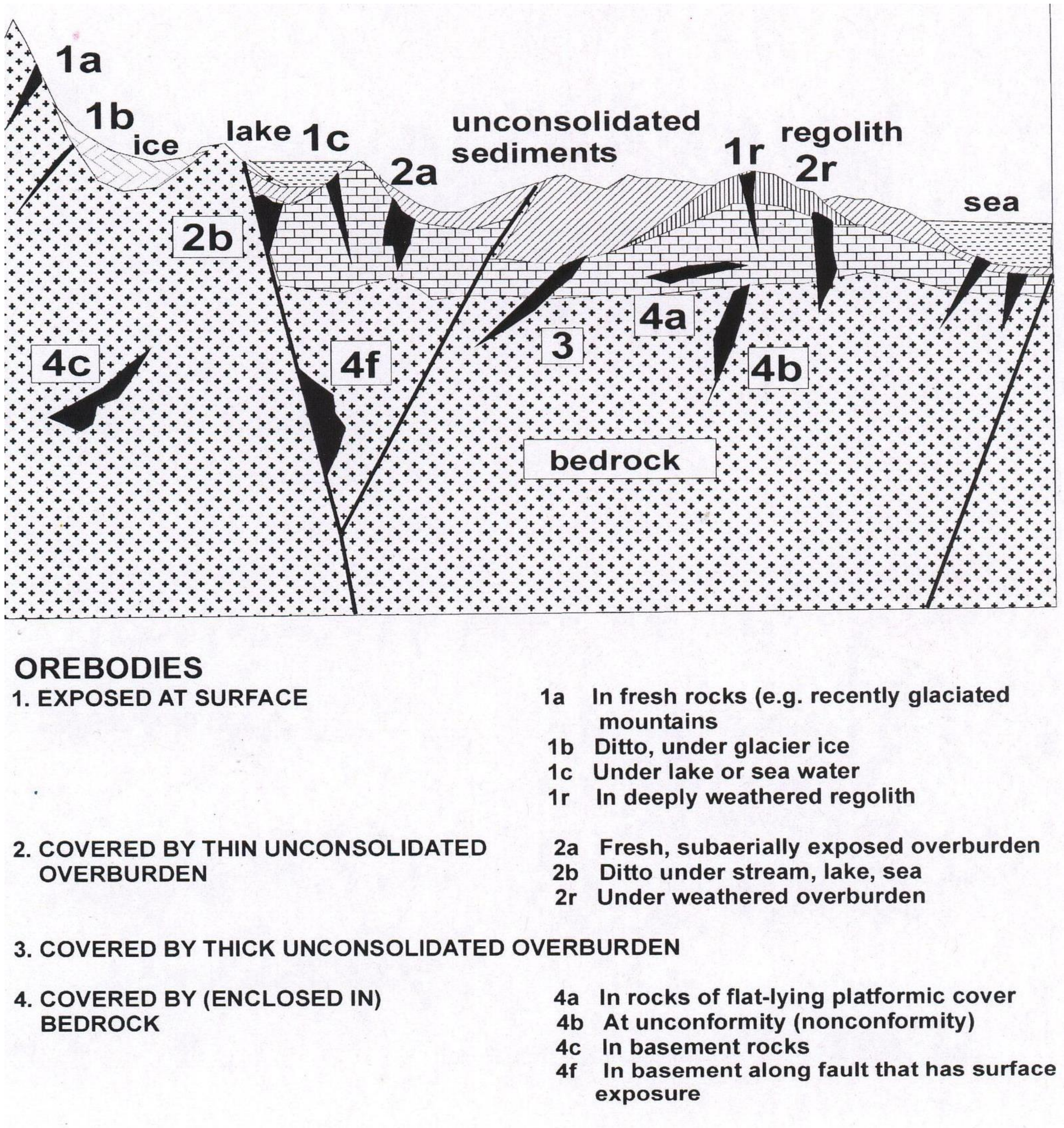

1a
1b
ice
lake
1c
2a
unconsolidated
sediments
1r
regolith
2r
sea
2b
4c
4f
3
4a
4b
bedrock
OREBODIES
1. EXPOSED AT SURFACE
1a In fresh rocks (e.g. recently glaciated mountains
1b Ditto, under glacier ice
1c Under lake or sea water
1r In deeply weathered regolith
2. COVERED BY THIN UNCONSOLIDATED OVERBURDEN
2a Fresh, subaerially exposed overburden
2b Ditto under stream, lake, sea
2r Under weathered overburden
3. COVERED BY THICK UNCONSOLIDATED OVERBURDEN
4. COVERED BY (ENCLOSED IN) BEDROCK
4a In rocks of flat-lying platformic cover
4b At unconformity (nonconformity)
4c In basement rocks
4f In basement along fault that has surface exposure

Figure 6.3

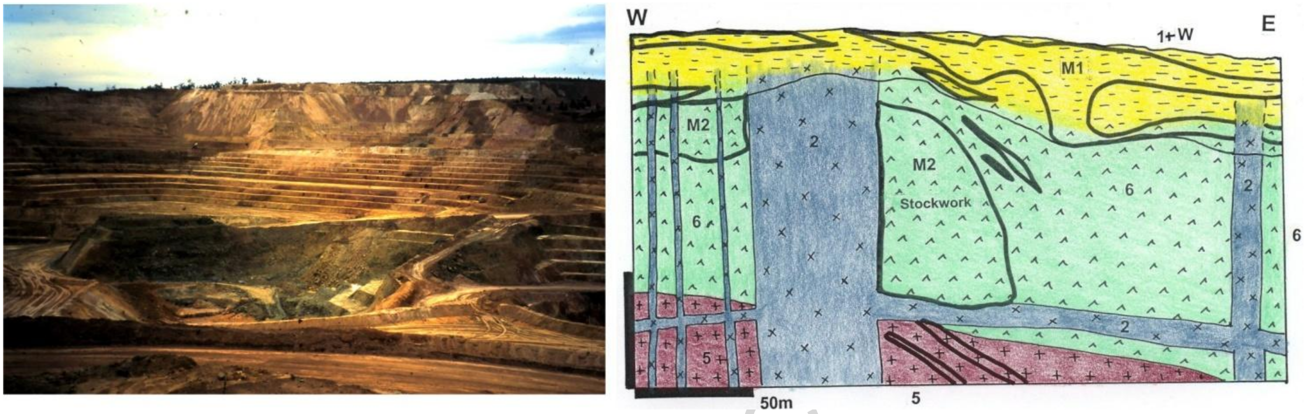


Figure 6.4

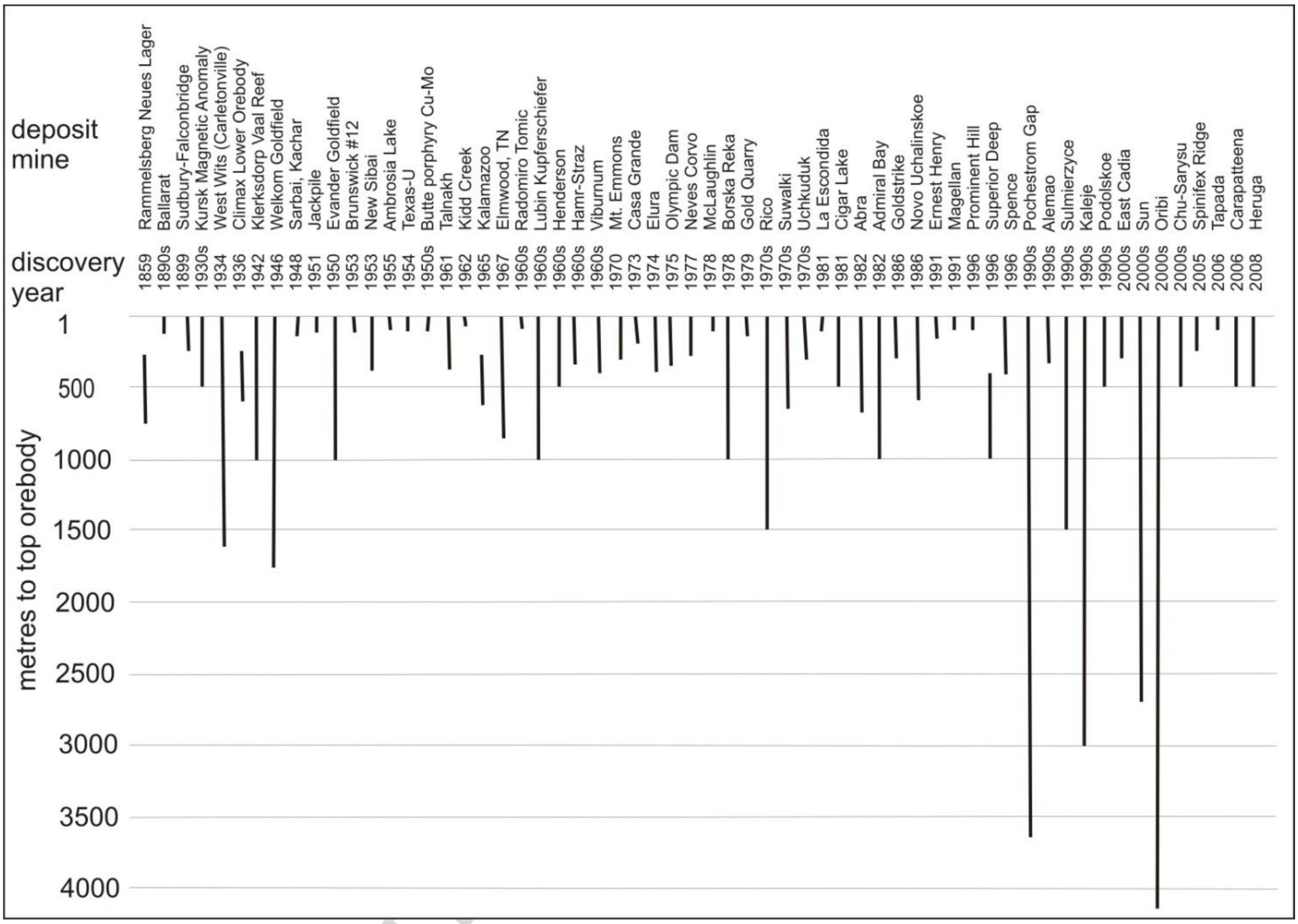

deposit
mine
discovery
year
metres to top orebody
1
500
1000
1500
2000
2500
3000
3500
4000
Rammelsberg Neues Lager 1859
Ballarat 1890s
Sudbury-Falconbridge 1899
Kursk Magnetic Anomaly 1930s
West Wits (Carletonville) 1934
Climax Lower Orebody 1936
Klerksdorp Vaal Reef 1942
Welkom Goldfield 1946
Sarbai, Kachar 1948
Jackpile 1951
Evander Goldfield 1950
Brunswick #12 1953
New Sibai 1953
Ambrosia Lake 1955
Texas-U 1954
Butte porphyry Cu-Mo 1950s
Talnakh 1961
Kidd Creek 1962
Kalamazoo 1965
Elmwood, TN 1967
Radomiro Tomic 1960s
Lubin Kupferschiefer 1960s
Henderson 1960s
Hamr-Straz 1960s
Viburnum 1960s
Mt. Emmons 1970
Casa Grande 1973
Elura 1974
Olympic Dam 1975
Neves Corvo 1977
McLaughlin 1978
Borska Reka 1978
Gold Quarry 1979
Rico 1970s
Suwalki 1970s
Uchkuduk 1970s
La Escondida 1981
Cigar Lake 1981
Abra 1982
Admiral Bay 1982
Goldstrike 1986
Novo Uchalinskoe 1986
Ernest Henry 1991
Magellan 1991
Prominent Hill 1996
Superior Deep 1996
Spence 1996
Pochestrom Gap 1990s
Alemao 1990s
Sulmierzyce 1990s
Kaleje 1990s
Podolskoe 1990s
East Cadia 2000s
Sun 2000s
Oribi 2000s
Chu-Sarysu 2000s
Spinifex Ridge 2005
Tapada 2006
Carapatteena 2006
Heruga 2008

Figure 6.5

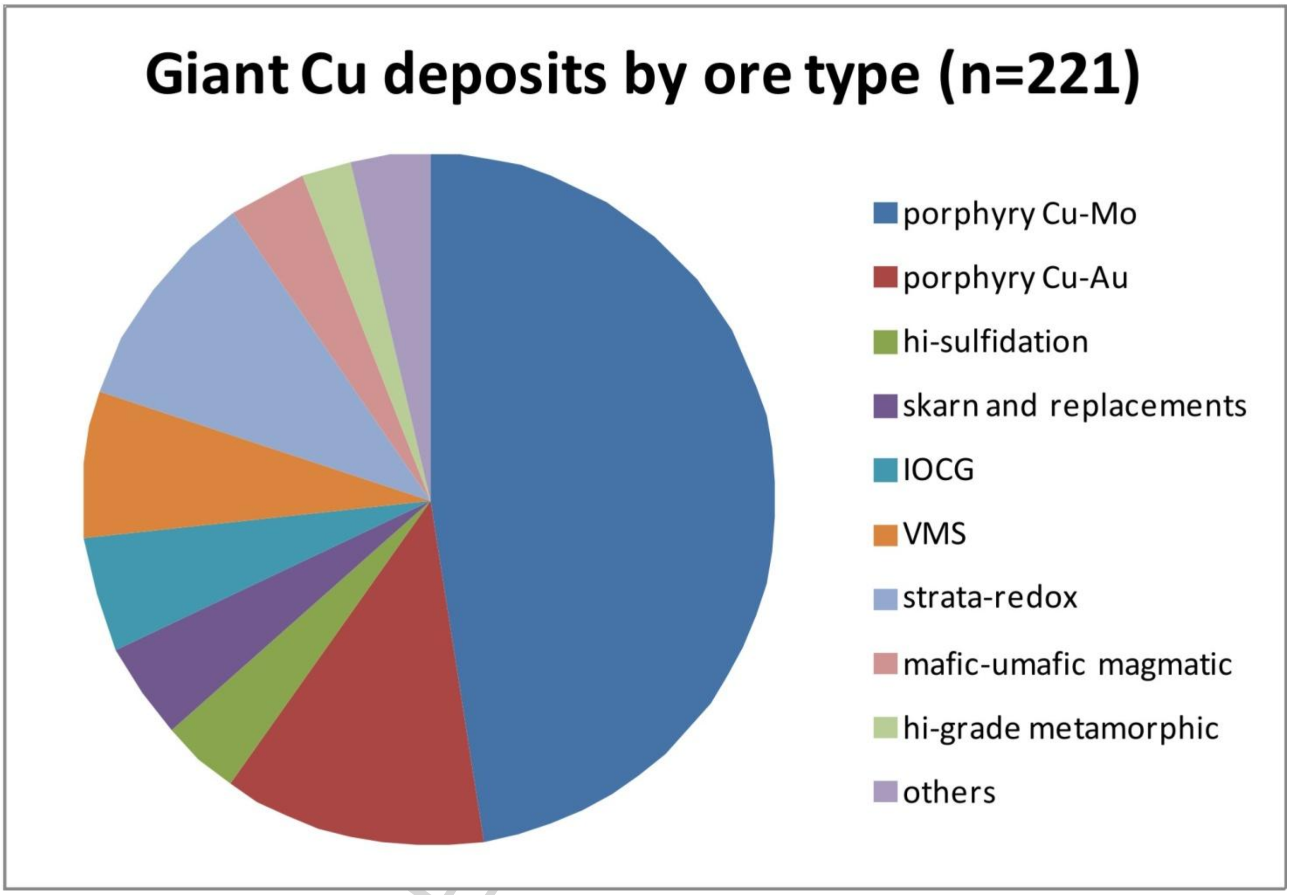

Giant Cu deposits by ore type (n=221)
porphyry Cu-Mo
porphyry Cu-Au
hi-sulfidation
skarn and replacements
IOCG
VMS
strata-redox
mafic-umafic magmatic
hi-grade metamorphic
others

Figure 7.1

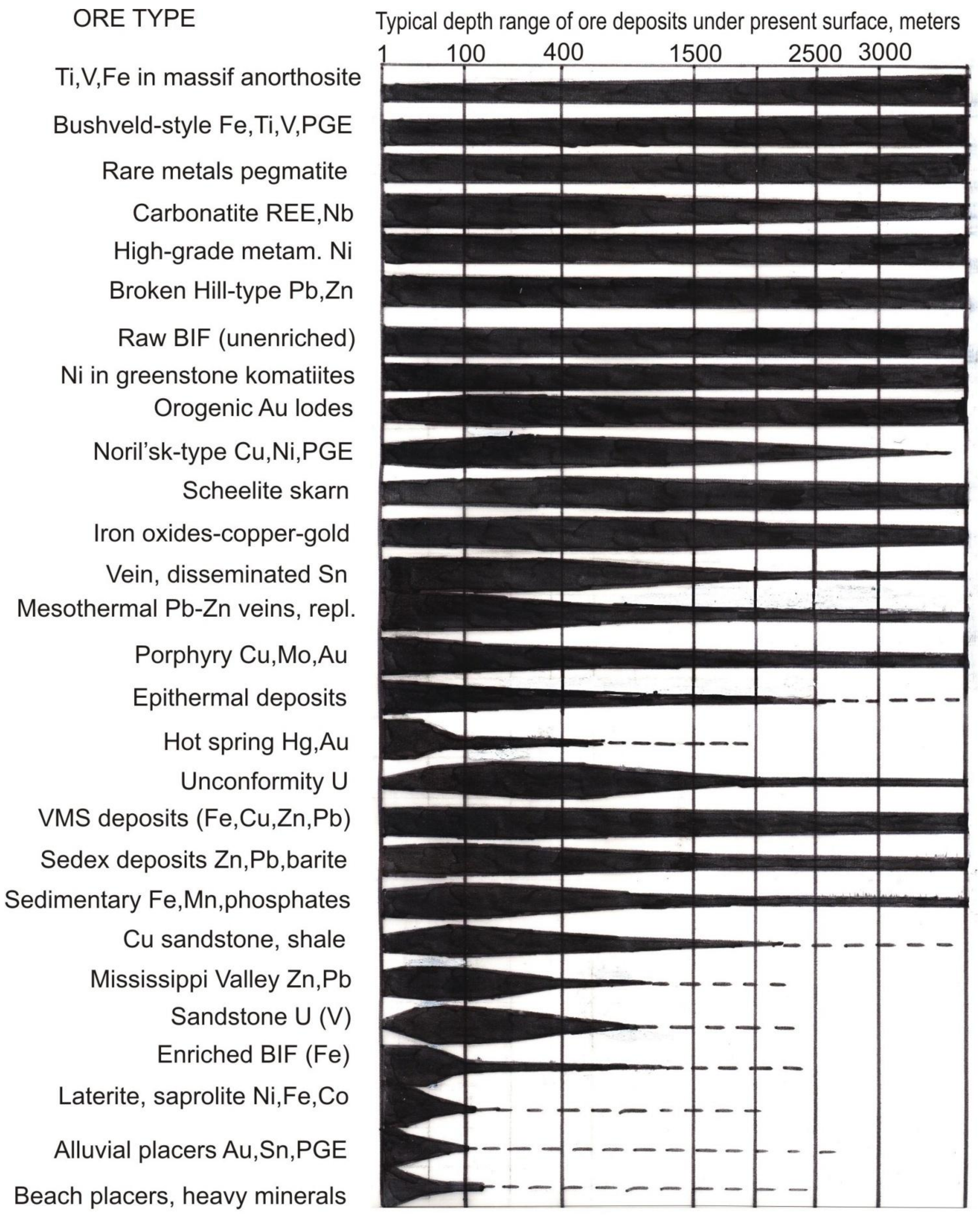

ORE TYPE
Typical depth range of ore deposits under present surface, meters
1
100
400
1500
2500
3000
Ti,V,Fe in massif anorthosite
Bushveld-style Fe,Ti,V,PGE
Rare metals pegmatite
Carbonatite REE,Nb
High-grade metam. Ni
Broken Hill-type Pb,Zn
Raw BIF (unenriched)
Ni in greenstone komatiites
Orogenic Au lodes
Noril'sk-type Cu,Ni,PGE
Scheelite skarn
Iron oxides-copper-gold
Vein, disseminated Sn
Mesothermal Pb-Zn veins, repl.
Porphyry Cu,Mo,Au
Epithermal deposits
Hot spring Hg,Au
Unconformity U
VMS deposits (Fe,Cu,Zn,Pb)
Sedex deposits Zn,Pb,barite
Sedimentary Fe,Mn,phosphates
Cu sandstone, shale
Mississippi Valley Zn,Pb
Sandstone U (V)
Enriched BIF (Fe)
Laterite, saprolite Ni,Fe,Co
Alluvial placers Au,Sn,PGE
Beach placers, heavy minerals

Figure 7.2

Table 2.1. Proposed terminology of delineated 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
Super-giant		
high super-giant	6.6×10^{12}	165 Mt
mid super-giant	3.3×10^{12}	82.5 Mt
low super-giant	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

Table 2.2. Crustal abundances (Clarkes in ppm), thresholds and range of the "large", "giant" and "super-giant" accumulations of metals (in metric tons of metal). Modified from Laznicka (1999)

metal	Clarke ppm	Large deposits low	mid	high	Giant deposits low	mid	high	Supergiant deposits 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^{-3}	1.3×10^{1}	5.2×10^{1}	9.1×10^{1}	1.3×10^{2}	5.2×10^{2}	9.1×10^{2}	1.3×10^{3}	5.2×10^{3}	9.1×10^{3}
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 are arranged by decreasing Clarkes

Table 2.3. Deposits and districts with giant accumulations of two or more "giants"

Metals	Number of entries	Example entry	Metals	Number of entries	Example entry
2 metals			**3 metals**		
Au,Ag	1	Pachuca, Mexico	Sn,Cu,Bi	1	Gejiu, China
Ag,Cu	3	Lubin (Kupferschiefer), Poland	Nb,REE,Th	1	Araxá, Brazil
Ag,Pb	6	Santa Eulalia, Mexico	Zr,Nb,Ta	1	Lovozero, Russia
Ag,Sn	3	Potosi, Bolivia	Ag,Pb,Zn	9	Sullivan, Canada
Ag,Zn	1	Rajpura-Dariba, India	Ag,Cu,Mo	3	Butte, Montana
As,V	1	Kerch Basin, Ukraine	Ag,Cu,Zn	3	Kidd Creek, Canada
Au,As	6	Vasil'kovskoe, Kazakhstan	Cu,Au,Mo	4	Petaquilla, Panama
Au,Cu	13	Grasberg, Indonesia	Cu,Ni,PGE	3	Sudbury, Canada
Au,Te	2	Cripple Creek, Colorado	PGE,Ni,Au	2	Merensky Reef, South Africa
Cr,PGE	2	Merensky Reef, South Africa	Ti,Fe,V	1	Bushveld magnetitite, SA
Cu,Mo	25	Chuquicamata, Chile	W,Bi,Te	1	Verkhnye Qairaqty, KZ
Cu,Co	2	Katanga, Congo	Zr,Nb,REE	1	Ilímaussaq, Greenland
Cu,Ni	1	Jinchuan, China	**4 metals**		
Fe,Mn	1	Urucúm, Brazil	Cu,Mo,Au,Ag	2	Bingham Canyon, Utah
Fe,V	1	Bakchar, Russia	Pb,Zn,Ag,Cu	1	Mount Isa, Australia
Mo,U	1	Billingen, Sweden	Zn,Pb,Ag,Bi	1	Brunswick #12, Canada
Nb,REE	1	Bayan Obo, China	REE,Y,Nb,Sc	1	Tomtor, Russia
Ni,Co	1	New Caledonia laterites	W,Sn,Bi,Be	1	Shizhouyuan, China
Pb,Sb	1	Bawdwin, Burma	**5 metals**		
Pb,Zn	12	Century, Australia	Cu,Mo,Ag,Au,Re	1	Chuquicamata, Chile
Cu,As	1	Rio Tinto, Spain	Cu,Zn,Mo,Ag,Bi	1	Antamina, Peru
Au,U	4	Klerksdorp, South Africa	Pb,Zn,Ag,Sb,Cd	1	Broken Hill, NSW
			Zn,Pb,As,Sb,Ag	1	Cerro de Pasco, Peru
			Cu,U,Au,Ag,REE	1	Olympic Dam, Australia

Table 2.4. Database entries of ore giants arranged by their footprint (area they occupy), from the smallest to the largest ones. These examples appear in Fig. 2.3.

Code	Size/shape complexity	Metal accumulation database entry	Dimension	No.of giants / metals	metals tonnages	References
ML	1S d	Matagami Lake VMS deposit-Quebec, Canada	~400 m	0	5.5 Mt Zn (Matagami cluster)	Sharpe 1965
AL	1S u	Almaden Hg deposit, Spain	~700 m	1/1	276,000 t Hg	Hernandez et al. 1999
MU	1S d	Murgul, Damar & Cakmakkaya Cu deposits, Turkey	~800 m	0	700 Kt Cu	A.I.Ercin 2011, site visit
WX	2L u	Woxi Sb-W-Au deposit, Hunan, China	~1400 m	2/2	1.67 Mt Sb ; 200 Kt W	Gu et al. 2012
CL	2E u	Climax Mo deposit, Colorado, USA	~1700 m	2/2	2.7 Mt Mo, 281 Kt W	White et al. 1981
ET	2E d	El Teniente Cu deposit, Chile	3 x 1.7 km	2/3	128 Mt Cu; 3.94 Mt Mo; 750 t Re	Camus, 1975
AR	2E s	Araxa, Barreiro Nb-REE deposit, Brazil	3.5 km diam.	2/3	19.9 Mt Nb; 17.5 Mt REE; 1.67 Mt Th	Barcellos, 1986
MK	2S d	Mankayan Cu-Au cluster, Luzon, Philippines	~4 km	2/2	8.38 Mt Cu; 1200 t Au	Hedenquist et al. 1998
CD	2S m	Cadia Valley Cu-Au deposit, NSW, Australia	6x3 km	1/3	8 Mt Cu; 160 Kt Mo; 1368 t Au	Wood, 2012
OD	2E u	Olympic Dam Cu,Au,U,Ag,Fe,REE deposit, South Australia	6 x 3 km	1/4	78.5 Mt Cu; 1.99 Mt U; 2969 t Au; 13311 t Ag	Reynolds, 2001
BQ	2L m	Bousquet camp-Au, Quebec, Canada	~7 km	1/1	694 t Au	Marquis et al. 1990
BH	2L u	Broken Hill-Pb,Zn,Ag, NSW, Australia	~8 km	1/5	Pb 30 Mt ; Zn 27 Mt ; Cd 120 Kt ; Sb 57 Kt ; Ag 42.5 Kt	Haydon & McConachy, 1987
SE	3E m	Sulphurets camp-Au,Cu, British Columbia, Canada	15 x 15 km	4/5	4.5 Mt Cu; 2654 t Au; 291 Kt Mo; 11639 t Ag; 106 t Re	Jones, 2012
OT	3L s	Oyu Togoi Trend- Cu,Au, Gobi, Mongolia	25 km	5/3	39.05 Mt Cu ; 108 Kt Mo ; 2429 t Au	Crane & Kavalieris, 2012
CH	3S m	Chuquicamata-Calama district-Cu,Mo, Chile	30 x 12 km	5/5	130 Mt Cu; 8.51 Mt Mo; 103 Kt Ag; 277 t Au; 500 t Re	Rivera et al. 2012
ML	3L m	Mother Lode (central) district-Au, CA, USA	~50 km	2/1	415 t Au (803 t Au in 130 km belt)	Landefeld, 1988
CT	3L u	Carlin Trend (main portion)-Au, Nevada, USA	~60 km	2/1	3800 t Au	Theodore et al., 2003
WK	3S u	Welkom Goldfield-Au,U, South Africa	60 x 30 km	1/1	16196 t Au	Minter et al. 1986
SU	3E m	Sudbury Complex-Ni,Cu, Ontario, Canada	65 x 35 km	2/3	19.8 Mt Ni; 17.8 Mt Cu; 1933 t PGE	Eckstrand, 1996
MR	3E u	Merensky Reef-PGE, Rustenburg segment, South Africa	~80 km	1/4	6.315 Mt Ni; 2.65 Mt Cu; 26161 t PGE; 1192 t Au	Cawthorn et al. 2002
SF	4S m	Sierra Nevada Foothills Au belt (veins+placers),CA, USA	~270 km	2/3	3100 t Au	Landefeld 1988
BM	4S m	Battle Mountain-Eureka gold belt, Nevada, USA	~320 km	2/1	3270 t Au	Sillitoe, 2008
EM	4S m	El Indio-Maricunga Au belt, Chile	~400 km	3/4	2519 t Au; 4.9 Mt Cu; 257 Kt Mo; 21600 t Ag	Sillitoe, 2008
CP	4S m	Central African Copperbelt-Cu,Co, Zambia & Congo	~440 km	14/3	190 Mt Cu; 11.3 Mt Co; 8.54 Mt Zn	Selley et al., 2005
MC	4S m	Middle Cauca gold belt, Colombia	~300 km	1/1	498 t Au	Sillitoe, 2008
AT	4E u	Athabasca Basin-U, Saskatchewan, Canada	450 x 220 km	1/1	610 Kt U	Kyser et al. 2000
WW	4E u	Witwatersrand Basin-Au,U, South Africa	470 x 250 km	7/2	109 Kt Au; 593 Kt U	Frimmel et al. 2008
HM	4E u	Hamersley Basin-Fe, Western Australia	600 x 200 km	3 styles/1	19.5 Bt Fe (~60% Fe+ hematite)	Harmsworth et al. 1990
KB	4E u	Kupferschiefer (Poland & Germany) Cu Basin	600 x 300 km	5/3	200 Mt Cu; 5.2 Mt Pb; 190 Kt Ag	Borg et al., 2012
TT	5S m	Tintina gold province, Alaska and Yukon	~1020 km	3/1	1612 t Au	Sillitoe, 2008

ZB	5E u	Zechsten Basin, W & C. Europe-Cu,Ag	1500 x 800 km	5/3	200 Mt Cu; 5.2 Mt Pb; 190 Kt Ag	Borg et al., 2012
BT	5S m	Bolivian (& Peru, Argentina) Sn-Ag belt	~1400 km	6/4	5.1 Mt Sn; 175 Kt Ag; 5.9 Mt Pb; 55 Kt Bi	Arce-Burgoa & Goldfarb, 2009
MX	5S m	Mexican Silver Belt	~1500 km	12/2	315 Kt Ag; 900 t Au (Pb & Zn excluded)	Clark et al., 1979
CC	5S u	Clarion-Clipperton Mn-nodule „field", high-grade; central Pacific	~2400 km	1/6	on 2.5 km^2 sea floor: 5.76 Mt Mn; 240 Mt Ni; 46 Mt Co; 198 Mt Cu; 26 Mt Zn	Piper & Hatch, 1989
AP	6S m	America's Pacific Cu belt, Alaska to Patagonia	~15000 km	~76/4	1662 Mt Cu plus Mo,Au,Ag	Sillitoe, 2012

EXPLANATIONS: Column 1, locality codes as shown in Fig. 2-3; Column 2, Size class: 1=0.1-1 km; 2=1-10 km; 3=10-100 km; 4=100-1000 km; 5=1000-10,000 km; 6=10 Kkm +. Shape: L=linear; S=semi-linear; E=equidimensional to irregular. Complexity: u=internally uniform deposits/groupings; d=broadly syndepositional ore doublets; s=superimposed ore doublets; m=mixed ore style populations. Column 5: Number of giants/metals in an entry, e.g. 5/2=5 giants containing 2 metal accumulations. Tonnages: t=tons (metric), Kt=thousand tons, Mt=million tons, Bt=billion tons.

Table 3.1. Numbers of super-giant and giant deposits and cumulative quantities of metals they contain

metal	number of supergiants	cumulative tonnage	number of giants	cumulative tonnage	number of giants and supergiants	cumulative tonnage	number of years at 2011 prod.	2011 world mine production
Ag	2	256,000	117	1,786,841	119	2,042,841	60.44	33,800
As	3	3,900,000	26	17.491.200	29	21,391,200	543.4	39,364
Au	20	119,127	258	148,946	278	268,073	99.3	2,700
Be			1	170,000	1	170,000	708.3	240
Bi	1	216,000	9	417,880	10	633,880	74.6	8,500
Cd			2	296.000	2	296.000	13.8	21,500
Co			2	12,800,000	2	12,800,000	133.3	96,000
Cr	2	21,699,000,000	1	112,800,000	3	21,811,800,000	2908.2	7,500,000
Cu	26	1,466,720,000	236	1,715,690,900	262	3,182,410,900	197.7	16,100,000
Fe	3	332,000,000,000	20	246,723,000,000	23	578,723,000,000	413.3	1,400,000,000
Hg	5	617,000	12	254,000	17	871,360	451.5	1,930
In			1	5,000	1	5,000	7.7	650
Li			5	21,116,000	5	21,116,000	621.1	34,000
Mn	4	14,650,000,000	9	4,136,000,000	13	18,786,000,000	1,341.9	14,000,000
Mo	14	26,254,000	152	40,942,483	166	67,196,483	268.8	250,000
Nb	1	57,000,000	2	12,200,000	3	69,200,000	1,098.4	63,000
Ni	1	80,000,000	8	88,744,000	9	168,744,000	93.7	1,800,000
Pb	4	128,100,000	86	275,253,900	90	403,353,900	89.9	4,500,000
PGE	7	95,890	13	5,496	20	191,386	485.8	394
Re	2	3,550	7	4,550	9	8,100	165.3	49
REE			7	156,630,000	7	156,630,000	1,204.8	130,000
Sb	8	6,909,000	30	3,429,620	38	10,338,806	61.2	169,000
Sn	2	5,400,000	33	21,106,000	35	26,506,000	104.8	253,000
Ta			2	351,000	2	351,000	444.3	790
Te	3	38,700	7	14,481	10	53,181	354.5	150
Th			1	1,670,000	1	1,670,000	N/A	N/A
U	4	17,891,808	24	7,924,370	28	25,816,178	508.5	50,772
V	1	1,770,000,000	4	99,890,000	5	1,869,890,000	31,164.8	60,000
W			34	9,789,625	34	9,789,625	136	72,000
Y	1	30,000,000			1	30,000,000	4,266.8	7,031
Zr	1	360,000,000			1	360,000,000	255.3	1,410,000
Zn			47	536,897,860	47	536,897,860	43.3	12,400,000

Metal quantities are in metric tons of metal. 1271 entries include 119 super-giants. Uranium production is for year 2009.

Table 3.2. The largest geological accumulations of metals ("deposits")

metal	G	deposit/district/area	category	cntry	geotect division	ore type	age	metal tons	grade	other met	references
Ag	SG	Lubin-Glogów, Kupferschiefer	district	PL	Variscan Foreland Fore Sudetic Monocline	stratabound Cu sulfides at redox interface in black shale,sandstone	250-159	141,000 t	60 g/t	Cu>Pb,Zn	Blundell et al. 2003
Ag	SG	Potosi, Cerro Rico	complex deposit	BO	Andes, Cordillera Oriental Bolivian Tin Belt	swarm of bonanza-Ag epith.veins under lithocap, on top pf porph.-Sn	13.8-12.5	115,000 t	102 g/t	Sn>Bi,W	Rice et al. 2005
Ag	SG	Chuquicamata ore complex	zone/ district	CL	Andes, Precordillera Domeyko struct.zone	string of giant porphyry Cu-Mo in qz monzonite porphyry // fault	35-34	106,385 t	5 g/t	Cu>Mo	Sillitoe & Perelló, 2005
Ag	G	La Escondida	cluster	CL	Andes, Precordillera Domeyko struct.zone	cluster of supergene enriched porphyry Cu-Mo in qzmz porphyry	33.7-31	55,790 t	5 g/t	Cu,Mo	Padila et al. 2001
Ag	G	Cerro de Pasco	complex ore cluster	PE	Andes, Central Peru Mineral Belt	intermed.sulfidation veins, Pb-Zn limestone replacem.near diatreme	15-14	53,647 t		Zn,Pb>Cu>Bi	Baumgartner et al., 2009
Al	L	Piceance Basin oil shale by-product	district-strat.unit	US-CO	Colorado Plateau Green River Formation	low-grade Al in accessory dawsonite in oil shale	Eo	3.1 Bt	2.1%		Smith & Milton, 1966
Al	L	NW Jamaica karst	area/baux. provinc e	JA	Caribbean	unconsolidated gibbsitic karst bauxite in sinks on Eo limestone	T3-Q	1.5 Bt	26%	Ga	Bárdossy, 1982
Al	L	Weipa-Aurukun	district	AU-QL	Karumba Basin	lateritic plateau bauxite	Cr3-Ol	827 Mt	29.15 %		Freyssinet et al., 2005
Al	M	Vietnam Central Highlands	district to area	VI	Indochina Craton, Kon-tum Block regolith	young gibbsitic lateritic bauxite on Pl-Q basalt	Q	678 Mt	21.2 %	Fe,Ti	Bárdossy & Aleva 1990
Al	M	Boke-Goual plateaux	district to area	GN	West African Craton cover	gibbsitic lateritic bauxite on dissected plateau on diabase & sediments	Cr-Q	622 Mt	25 %	Fe,Ti	Bárdossy & Aleva 1990
As	SG	Kerch iron ore basin	basin	UK	Russian Platform cover	goethite, chlorite ironstone	J	2.2 Mt	0.13 %	Fe,V	Sokolov & Grigor'ev, 1974
As	SG	Olympic Dam	deposit	AU-SA	Gawler Craton Olympic Domain	trace As in breccia-hosted, hematite altered Cu,U,Au IOCG deposit	1,585	1.915 Mt	200 ppm	Cu,U,Au,Ag	Ehrig et al., 2012
As	G	Natal'ka gold mine	zone	RS	Omchak Terrane	orogenic-Au, quartz-sulfide veinlets in shear zone	136	1.5 Mt	0.4 %	Sb,Au	Goldfarb et al., 2005
As	G	Vasilkovskoe gold mine	deposit	KZ	Kipchak Superterrane	Au in arsenopyrite sheeted veins in granitoids	443	1.5 Mt	+1.3%	Au,Bi	Symons et al. 1990
As	G	Obuasi (Ashanti) gold	zone	GH	Birrimian orogen	orogenic Au, quartz-arsenopyrite lodes in shear in graphitic phyllite	Pp	1.2 Mt	2.7 %	Au	Goldfarb et al., 2005
Au	SG	West Wits Goldfield, Witwatersrand	cluster	SA	Kaapvaal Craton Witwatersrand Basin	gold disseminated in quartz con-glomerate horizons in clastics	Ar3	19,936 t	7.56 g/t	U	Frimmel et al., 2005
Au	SG	Welkom Goldfield, Witwatersrand	cluster to district	SA	Kaapvaal Craton Witwatersrand Basin	gold disseminated in quartz con-glomerate horizons in clastics	Ar3	16,196 t	11.6 g/t	U	Frimmel et al., 2005
Au	SG	Ertsberg-Grasberg	cluster	ID-PP	Western Papuan Arc	Grasberg porphyry Cu-Au envelo-	3.3-	6,380	0.58	Cu>Ag,Mo	Leys et al., 2012

		(Grasberg only)				ped by Cu-Au skarns	2.6	(2,909)	g/t (0.69 g/t)		
Au	SG	Muruntau	deposit	UZ	Tian Shan orogen, Central Kyzyl-kum	A system of quartz-gold veins in hornfelsed fine clastics	288-280	5,290	3.5 g/t	>>W,U	Goldfarb et al., 2005
Au	SG	Kolyma, Yana, Indigirka Basins, Magadan region	large area alluvials	RS	Russian Far East	placer gold in large number of stream channel gravels	T-Q	4,043			Goldfarb et al., 2005
Au	SG	Pebble	cluster	US-AK	Alaskan Cordillera, Kahitna Flysch Basin	2 zones of porphyry Cu-Au in granodiorite & hornfelsed turbidites	~90	3,337	0.34 g/t	Cu,Mo,Ag	Lang and Gregory, 2012
Au	SG	Olympic Dam (Roxby Downs)	deposit	AU-SA	Gawler Craton, Olympic Domain	disseminated Au in breccia-hosted hematite-altered IOCG deposit	~1585	2,906	0.32 g/t	Cu,U,Ag,REE	Ehrig et al., 2012
Be	G	Shizhouyuan, Dongpo district	cluster	CH-HN	South China Block Nanling Range	beryl, phenakite dissem.in greisen and skarn around granite stock	162-150	200 Kt	0.12 %	W,Sn,Mo,Bi,Pb,Zn,Ag	Lu et al., 2003
Be	L	Round Top Laccolith	deposit	US-TX	Sierra Blanca	trace & accessory Be minerals dissem.in alkal.rhyolite	36	92,800	58 ppm	Rb,Cs,Th	Price, 2004
Be	L	Nu Phao, Tam Dao distr., Bac Thai Province	cluster	VI	South China Plate	disseminated Be minerals in greisen and skarn	Tr3	84,000	0.1 %	W,Sn,Mo,Bi	Meinert, 2005
Be	M	Letitia Lake, Two Tom deposit	deposit	CN	Canadian Shield	disseminated & veinlet Be minerals in peralkaline granite complex	1,330	26,390	650 ppm		Miller, 1988
Be	M	Spor-Topaz Mountain	cluster	US-UT	Basin and Range	disseminated bertrandite with fluorite in rhyolite tuff & tuffite	6	24,000	0.3 %	F,U	Davis, 1991
Bi	SG	Verkhnye Kairakty (Qairaqty)	composite deposit	KZ	Altaides, Kipchak Arc	W,Bi stockwork in/above granite cupola and regolith	Cb3	216,000	0.024 %	W>Mo,Sn	Pollard et al. 2005 Russkikh & Shatov, 1996
Bi	SG	Nu Phao, Tam Dao distr., Bac Thai Province	cluster	VI	South China Plate	disseminated Bi minerals in greisen and skarn	Tr3	143,000	0.17 %	W,Sn,Mo,Be	Meinert, 2005
Bi	SG	NICO project	deposit	CN-NT	Canadian Shield, Bear Province	disseminated Bi,Ni,Co sulfides in schist: IOCG relative?	1,900-1,850	127,000	0.12 %	Ni,Co,As	Goad et al., 2000
Bi	SG	Antamina	composite deposit	PE	Andes, Cordillera Oriental, Peru	Zn-Cu exoskarn around intrusion with lesser porphyry-Cu	10	106,000	70 ppm	Zn,Cu>Ag,Au	Love et al., 2004
Bi	SG	Shizhouyuan	cluster	CH-HN	South China Block Nanling Range	Bi sulfides disseminated in greisen & skarn around granite stock	162-150	100,000	590 ppm	W,Sn,Mo,Be,PbZn,Ag	Lu et al., 2003
Cd	G	Jinding (Lanping)	cluster	CH-YU	Lanping-Simao Basin	disseminated Zn,Pb sulfides in sedim.rocks along thrust	130-110	176,000	0.01-0.2 %	Zn,Pb	Li and Kyle, 1997
Cd	G	Broken Hill, NSW	composite deposit	AU-NW	Curnamona Province	zone of overlapping massive Pb-Zn sulphide lenses in hi-grade metam.	1,690	120,000	380 ppm	Pb,Zn,Ag>Cu, Sb	Huston et al., 2006
Cd	L	Uchaly	composite deposit	RS-URL	Urals orogen, Magnitogorsk Arc	Cu,Zn,Pb massive sulphide VMS lenses in bimodal metavolcanics	365, 390	33,750	150 ppm	Zn,Cu>Pb,Ag, Au	Franklin et al. 2005
Co	G	Central African	metalloge-	CG,ZA	Lufilian Arc, Central	stratabound Cu & Co sulfides and	Np	11.3 Mt	0.1-	Cu	Hitzman et al. 2012

		Copperbelt	nic belt		Africa	oxides in metasediments			0.4 %		
Co	G	Kolwezi Nappe in Central African Cpbltt	cluster	ZA	Lufilian Arc, Central Africa	stratabound Cu & Co sulfides and oxides in metased.thrust slices	Np	2,396,000	0.33 %	Cu	Hitzman et al. 2012
Co	G	New Caledonia Ni laterites (global)	metalloge-nic belt	NC	Western Pacific	Co in asbolite in Mn-rich intervals in laterite over Oligocene peridotite	Mi-Q	2,500,000	0.15 %	Ni,Fe	Freyssinet et al. 2005
Co	L	Sudbury Complex	base of "basin"	CN-ON	Canadian Shield, Southern Province	Co in Fe-Ni-Cu massive & dissem. sulf. at base of impact melt sheet	1,850	659,000	0.04 %	Ni,Cu>PGE	Burrows and Lesher, 2012
Co	L	Duluth Complex NW margin	intrusion contact	US-MN	Mid-Continent Rift (USA)	trace Co in mass. & dissem. Fe-Ni-Cu sulf. at base of troctolitic intrus.	1,100	554,000	0.014 %	Cu>Ni>PGE	Burrows and Lesher, 2012
Cr	SG	Bushveld chromitite layers, prod.& reserve	intrusion layers	SA	Kaapvaal Craton Bushveld Complex	set of magmatic-stratiform chromitite layers, most in pyrox.	2,060	2.7 Bt	28 %	PGE	Cawthorn et al. 2005
Cr	SG	Great Dyke chromitite layers	intrusion layers	ZB	Zimbabwe Craton Great Dyke	set of magmatic-stratiform chromitite layers, most in dunite	2,514	899 Mt	36.42 %		Cawthorn et al. 2005
Cr	G	Kempirsai-Khromtau	belt	KZ	Urals orogen, Sakmara Arc	zone of podiform & layered chro-mitite in ophiolitic dunite	S	112.8 Mt	37.6 %		Cawthorn et al. 2005
Cu	SG	Central African Copperbelt	metalloge-nic belt	CG,ZA	Lufilian Arc	stratabound Cu & Co sulfides and oxides in metasediments	Np	213 Mt	0.7-4.5 %	Co>Zn,Pb,U,Ge	Hitzman et al., 2012
Cu	SG	Rio Blanco-Los Bronces (Andina & Disputada)	cluster	CL	Andes, Cordillera Principal, central Chile	cluster of porphyry Cu-Mo deposits most in tourmaline matrix breccias	5.4	206.7 Mt	0.6	Mo>>Ag,Au	Toro et al. 2012
Cu	SG	Chuquicamata Cu zone	district/ zone	CL	Andes, Cordillera Domeyko, Chile	number of enriched to hypogene Cu-Mo deposits in 30km N-S trend	35-34	130 Mt	0.59 %	Mo>Ag>Au	Rivera et al. 2012
Cu	SG	El Teniente (Braden)	composite deposit	CL	Andes, Cordillera Principal, Chile	porphyry Cu-Mo in biotitized andesite, mafic dikes, diorite	6.3-4.4	128.5 Mt	0.63 %	Mo	Sillitoe and Perelló, 2005
Cu	SG	La Escondida (includes Zaldivar)	cluster	CL	Andes, Cordillera Domeyko, Chile	cluster of porphyry Cu-Mo depo-sits with strong oxid. & chalcoc.zone	34-31	97.64 Mt	0.57-0.8 %	Mo	Richards et al., 2001
Cu	SG	Lubin-Glogów (Polish Kupferschiefer)	district	PL	Fore-Sudetic Monocline	stratabound disseminated Cu sulfides in sedim. at redox interface	250-159	91 Mt	2 %	Ag,Pb,Zn>> Au,PGE	Borg et al. 2012
Cu	SG	Olympic Dam (Roxby Downs)	deposit	AU-SA	Gawler Craton, Olympic Domain	dissem.Cu sulfides in seric.-hemat. altered breccia in granite; IOCG	1,585	78.523 Mt	0.82 %	U,Au,Fe,REEAg, As	Ehrig et al. 2012
Cu	SG	Collahuasi	cluster	CL	Andes, Cordillera Domeyko, Chile	cluster of porphyry Cu-Mo depo-sits with strong oxid. & chalcoc.z		77.54 Mt	0.85 %	Mo,Ag>Au	Sillitoe and Perelló, 2005
Fe	G	Corumbá-Mutún	district	BR+BO	Jacadigo Group	Neoproter. bedded hematitic ironstone in diamictite association	990-950	40.88 Bt	50 %	Mn	Arce-Burgoa & Goldfarb, 2009
Fe	G	KMA-Kursk Magnetic Anomaly	"basin"	RS	Russian Platform	enriched and raw BIF under Phanerozoic platformic cover	1,900	35 Bt	56 %		Chaykin, 1985
Fe	G	Hamersley Province enriched hematite ore	"basin"	AU-WA	South margin of Pilbara Block	superg. & hydroth. enriched hematite over raw BIF	2,600-2,450	19.5 Bt	60+ %		Harmsworth et al., 1990
Fe	G	Krivoi Rog, enriched & raw magnetite BIF	"basin"	UK	Ukrainian Shield	superg. hem atite, hydroth. enri-ched magnetite, raw magnetite	Pp	19.2 Bt	25-60 %		Belevtsev et al., 1983

						BIF					
Fe	G	Mesabi Range	"basin"	US-MN	Canadian Shield, Southern Province	superg. hem atite, hydroth. enriched magnetite, raw magnetite BIF	Pp	15 Bt	25-55 %		Marsden, 1968
Fe	G	Bakchar	sediment. layer	RS-SI	West Siberian Basin	horizon of bedded sedim. layers of hematite, siderite, leptochlorites	Cr3	10.5 Bt	37.4 %	V	Tomskaya Kompleksnaya Ekspedicia, 1965
Ga	M	Dak Nong bauxite area. Mnong Plateau	area	VI	Indosinian Massif, regolith	trace Ga in gibbsitic lateritic bauxite on Pl-Q basalt	Q	96,444 t	36 ppm	Al,Fe,Ti,Ge	Bárdossy and Aleva, 1990
Ga	S	Thor Lake, Nechalacho zone	deposit	CN-NW	Canadian Shield, Slave Province	trace Ga in peralkaline intrusion	2,094	8,422 t	93-121 ppm	Ta,Nb,Be,Th	Trueman, 1983
Ga	S	Jamaica red muds (tailings)	industrial waste	JA	Caribbean	trace Ge recoverable from "red muds" after bauxite purification	Q	1,500 t	65 ppm	Al,Fe,Ti	Bárdossy, 1982
Ge	L	Dak Nong bauxite area. Mnong Plateau	area	VI	Indosinian Massif, regolith	trace Ga in gibbsitic lateritic bauxite on Pl-Q basalt	Q	96,444 t	36 ppm	Al,Fe,Ti,Ga	Bárdossy and Aleva, 1990
Ge	L	Red Dog	cluster	US-AK	Cordilleran orogen, Brooks Range	trace metal in Zn>Pb sulfides in sedex orebodies in black slate	338	18,670 t	100 ppm	Zn,Pb,Ag	Leach et al., 2005
Ge	L	Kipushi (King Leopold) Mine	deposit	ZA	Lufilian Arc, Central African Copperbelt	Zn,Pb,Cu sulfides & oxides in fault and replace breccia	450	18,000 t	0.03 %	Zn,Pb,Cu,Ag	Hitzman et al. 2012
Hf	L	Toongi (Dubbo) project	deposit	AU-NW	Lachlan Foldbelt, anorogenic intrusions	disseminated rare metals in alkaline trachyte stock	J	85,000 t	0.034 %	Zr,Nb,REE, Th	Alkane NL website, 2002
Hf	M	Katuga (Katuginskoe)	deposit	RS	Aldan Shield west	disseminated rare metals in alkaline metasomatites in shear zone	2,100	17,000 t	167 ppm	Zr,REE,Nb, Ta,Th	Arkhangel'skaya et al., 1993
Hf	M	Strange Lake	cluster	CN-QU	Canadian Shield	disseminated rare metals in peralkaline intrusion	1,190	16,380 t		REE,Be,Ta Nb	Miller, 1988
Hg	SG	Almaden Mine	deposit	SP	Variscan (Hercynian) orogen	disseminated cinnabar in quartzite beds in shale near mafic breccia	S	276 Kt	8-1 %		Hernandéz et al., 1999
Hg	SG	Idrija	deposit	SV	Tethides, Alpine orogen	early sedex? cinnabar, remobilized along thrust, faults	Tr-T	170 Kt	1.14 %		Bercé, 1958
Hg	SG	Monte Amiata (Abbadia San Salvatore)	cluster	IT	Tethydes, Appenines of Tuscany	cinnabar as hot sporing impregn. and replacem. in faulted limestone	Q	80 Kt	0.8 %		Pichler, 1970 bk
Hg	SG	Huancavelica mines	cluster	PE	Andes, Central Peru Mineral Belt	dissem. cinnabar in sand-stone & limestone replac.	Mi-Pl	51 Kt			Noble & Vidal, 1990
Hg	SG	Muyouchang, Wuchuan County	cluster	CH	Guizhou Hg belt	disseminated and replacive cinnabar in limestone along faults	MZ? in Cm	40 Kt	0.26 %	As	He and Zeng, 1992
In	G	Toyoha Mine	deposit	JP	Japan Island Arc, Hokkaido	Intermediate sulfidation Zn,Pb veins	2.9-1.4	5,000 t	310 ppm	Pb,Zn,Ag	Shikazono, 1975
In	L	Uchaly mine	2 deposits set	RS-URL	Urals orogen, Magnitogorsk Arc	Zn-Cu VMS lenses in bimodal metavolcanics	365 or 390	3,150 t	15 ppm	Cu,Zn,Pb	Franklin et al. 2005
In	L	Freiberg, Saxony	cluster	GE	Variscan Orogen, Erzgebirge	1100 Ag-rich polymetallic veins in gneiss cupola	Pe-MZ	700 t	176 ppm	Pb,Zn,Ag,Sb, Cu,As	Baumann, 1976
Li	G	Salar de Uyuni	playa basin	BO	Andes, Altiplano	Li dissolved in playa brine	Q	8.9 Mt	80-1150	B	Ferrell, 1985

									ppm		
Li	G	Salar de Atacama	playa basin	CL	Andes, Altiplano	Li dissolved in playa brine	Q	4.6 Mt	2,550 ppm		Ferrell, 1985
Li	G	Salar de Hombre Muerto	playa basin	AR	Andes, Altiplano	Li dissolved in playa brine	Q	3.36 Mt	720 ppm		Minerals Yearbook, 1996
Li	G	Kings Valley, McDermitt Caldera	deposit	US-NV US-OR	Basin-and-Range	Li in hectoritein lake beds in caldera	18-16	2.256 Mt		U,Hg	Rytuba & Glanzman, 1985
Li	L	Cinovec-Zinnwald	deposit	CZ	Variscan orogen, Erzgebirge	Li in zinnwaldite disseminated in leucogranite	Pe	1.43 Mt	0.25 %	Sn,Rb,Cs	Štemprok et al., 1995
Mn	SG	Kalahari Mn Basin	“basin”	SA	Kaapvaal Craton, SW Transvaal subbasin	3 sedim. beds of braunite-kutnahorite above siliceous BIF	2,200	4.94 Bt	38 %		Tsikos et al., 2003
Mn	SG	South Ukrainian Mn Basin (Nikopol-Tokmak)	“basin”	UK	Ukrainian Shield cover	one or more sedim.beds of Mn carbonates and oxides	Ol	2.2 Bt	22-29 %		Varentsov & Rakhmanov, 1974
Mn	SG	Molango	district	MX	Cordillera Occidental, Mexico	low-grade Mn carbonate beds among limestone	J3	1.6 Bt	10 %		Okita, 1992
Mn	G	Chiatura mines	cluster	GA	Caucasus	Mn oxides and carbonates sedimentary beds	Ol	600 Mt	20 %		Varentsov & Rakhmanov, 1974
Mn	G	Moanda, enriched ore on plateaux	cluster	GO	Okouma Plateau	microconcretionary Mn oxides in laterite on Mn-carbonate protore	T3-Q	275 Mt	35 %		Freyssinet et al. 2005
Mo	SG	Chuquicamata Cu-Mo zone	district/ zone	CL	Andes, Precordillera, Cordillera Domeyko	30 km N-S zone of porphyry Cu-Mo deposits and clusters	35-34	8.510 Mt	0.04 %	Cu>Ag,Au	Rivera et al. 2012
Mo	SG	El Teniente mine	deposit	CL	Andes, Mi-Pl Farellones Arc	porphyry Cu-Mo in biotitized andesite, mafic dikes, diorite	6.3-4.4	3.94 Mt	0.019 %	Cu>Ag	Sillitoe and Perelló, 2005
Mo	SG	Pebble	cluster	US-AK	Kahiltna Flysch Basin	2 zones of porphyry Cu-Au in granodiorite & hornfelsed turbidites	90	2.8 Mt	0.025 %	Cu,Au,Ag	Lang and Gregory, 2012
Mo	SG	Climax	composite deposit	US-CO	Colorado Rocky Mountains	3 coaxial shells of Mo stockworks above siliceous porphyry cupolas	30	2.7 Mt	0.2 %	W	Wallace, 1995
Nb	SG	Morro do Seis Lagos	deposit	BR	Amazon Craton cover	pyrochlore disseminated in regolith and in carbonatite	MZ T-Q	57 Mt	2 %	REE	de Souza, 1996
Nb	SG	Araxa, Barreiro carbonatite	composite deposit	BR	Brazilian Shield, fringe of Parana Basin	pyrochlore disseminated in residual ochre and in carbonatite breccia	Cr	19 Mt	1.42 %	REE,Th,U	Wooley, 1989
Nb	G	Tomtor	composite deposit	RS	Siberian Platform Udgy Paleorift	Nb,REE,Sc minerals in reworked residuum and in carbonatite	Np, Pe	10 Mt	5.4-3 %	REE,Ta,Sc	Kravchenko & Pokrovsky, 1995
Nb	G	Lovozero massif	intrusion layers	RS	Baltic Shield, Kola, Devonian intrusions	Nb,Ta,REE minerals disseminated in layers of agpaitic nephel.syenite	370	7 Mt		Zr,REE,Ta	Kogarko, 1987
Nb	G	Bayan Obo	composite deposit	CH	North Margin North China Craton	pyrochlore disseminated in alkaline metasomatite in marble	1,354 420	2.2 Mt	0.2 %	Fe,REE,Th	Chao et al., 1997
Ni	SG	New Caledonia Ni laterites, global	metallo-genic belt	NC	Western Pacific	Ni in ochre and hydrosilicates in laterite & saprolite on peridotite	Mi-Q Ol	80 Mt	7-1.2 %	Fe,Co	Freyssinet et al. 2005
Ni	G	Noril'sk-Talnakh	district	RS	NW margin of	Ni,Cu sulfides at base of gabbro	248	28.045 Mt	1.77	Cu,PGE,Co	Burrows and Lesher,

					Siberian Platform	sills & replacements in skarn			%		2012
Ni	G	Sudbury Complex	base of "basin"	CN-ON	Canadian Shield, Southern Province	Co in Fe-Ni-Cu massive & dissem. sulf. at base of impact melt sheet	1,850	19.776 Mt	1.2 %	Cu,Co,PGE	Burrows and Lesher, 2012
Ni	G	Bushveld PGE pyroxenite layers	composite intrusion	SA	Kaapvaal Craton	disseminated accessory pentlandite in PGE-bearing pyroxenite layers	2,060	15.015 Mt	0.13 %	PGE,Cu	Cawthorn et al. 2005
Ni	G	Jinchuan	cluster	CH	North China Craton west	dissem.Ni sulfides in 5 faulted ultramafic intrusions	827 1508	5.459 Mt	1.06 %	Cu,Co,PGE	Burrows and Lesher, 2012
Pb	SG	SE Missouri lead region	area	US-MO	Ozark Uplift, North American Interior Plains	cluster & zone of MVT-type galena >>Zn,Cu,Co sulfides in Cm limest	Pe	49 Mt	6 %	Zn,Cu,Co,Ag	Leach et al., 2005
Pb	SG	McArthur River, HYC deposit	deposit	AU-QL	Mout Isa Inlier , McArthur Basin	set of siliceous layers in black shale with finely dissem.Pb-Zn sulf;sedex	1,638	32 Mt	4.1 %	Zn,Ag	Large et al., 2005
Pb	SG	Broken Hill lode	deposit/ zone	AU-NW	Curnamona Craton Broken Hill domain	7 overlapping lenses of massive Pb,Zn sulfides in hi-grade gneiss	1,690	30 Mt	10 %	Zn,Ag,Cu,Sb	Large et al., 2005
Pb	SG	Mount Isa-Hilton zone	zone	AU-QL	Mount Isa Inlier West	N-S zone of stratabound Zn-Pb (sedex?) orebodies in dolom.slate	1,655	20.72 Mt	5.6 %	Zn,Ag,Cu	Large et al., 2005
Pb	SG	Howard's Pass (Summit Lake)	zone	CN-NW	Canadian Cordillera, Mackenzie Mts.	zone of very fine sedex Pb-Zn sulfides in silicified slate	S1	17.1 Mt	2 %	Zn,Ag	Leach et al. 2005
PGE	SG	Bushveld, UG2 chromitite reef	igneous layer	SA	Kaapvaal Craton, Bushveld Complex	PGE minerals disseminated in UG2 chromitite layer in bronzitite	2,060	32,730 t	5.7 ppm	Cr	Cawthorn et al. 2002
PGE	SG	Bushveld, Merensky Reef	igneous layer	SA	Kaapvaal Craton, Bushveld Complex	PGE minerals with Fe,Ni,Cu sulf. disseminated in bronzitite layer	2,060	26,161 t	6.214 ppm	Ni,Cu,Au	Cawthorn et al. 2002
PGE	SG	Noril'sk-Talnakh	district	RS	NW margin of Siberian Platform	Pd>Pt minerals with Ni-Cu sulfides at base of gabbro sills & metasom.	248	13,133 t	10 ppm	Ni,Cu,Co,Au	Burrows and Lesher, 2012
PGE	SG	Stillwater Complex, J-M Reef	igneous layer	US-MT	Beartooth Mountains	Pd>Pt minerals with Ni-Cu sulfides dissem. in bronzitite pegm. layer	2,705	10,961 t	19 ppm	Ni,Cu,Au	Cawthorn et al. 2005
PGE	SG	Bushveld, Platreef	belt	SA	Kaapvaal Craton, Bushveld, North Prong	PGE minerals with Fe,Ni,Cu sulf. at pyroxenite-BIF & carbonate contact	2,060	6,582 t	4.121 ppm	Ni,Cu,Au	Cawthorn et al. 2002
Re	SG	Dzhezkazgan	district	KZ	Kazakh-Mongol Arc Sarysu Sub-basin	dissem. Cu sulfides in reduced sandstone beds in red beds	309-299	2,800 t	1.4 ppm	Cu,Pb,Zn,Ag	Box et al. 2012
Re	SG	Mansfeld-Sangerhausen Kupferschiefer	cluster	GE	Variscan orogen foreland	stratabound Cu sulfides in black shale & sandst. at redox interface	Pe3	1,575 t	21 ppm	Cu,Ag	Borg et al. 2012
Re	SG	El Teniente	composite deposit	CL	Andes, Mi-Pl Farellones Arc	Re in molybdenite in porphyry Cu-Mo in biotitiz,mafics & diorite	6.3-4.4	750 t	3.6 ppm	Cu,Mo,Ag	Sillitoe and Perelló, 2005
Re	SG	Almalyk (Olmalyk)	cluster	UZ	Tian Shan orogen, Kurama Range	Re in molybdenite in porphyry Cu-Mo-Au	314	566 t	0.9 ppm	Cu,Mo,Ag,Au	Yakubchuk et al., 2012
REE	G	Bayan Obo	composite deposit	CH	North Margin North China Craton	bastnasite & monazite dissem.in alkal.metasomatites in marble	1354 420	45 Mt	3.36 %	Fe,Nb	Chao et al., 1997
REE	G	Morro do Seis Lagos	deposit	BR	Amazon Craton cover	Nb & REE minerals disseminated in regolith over carbonatite	T-Q/MZ	43.5 Mt	1.6 %	Nb	de Souza, 1996
REE	G	Tomtor complex	composite	RS	Siberian Platform	Nb,REE,Sc minerals in reworked	Np,	25 Mt		Nb,Ta,Sc,Th	Kravchenko &

			deposit		Udgy Paleorift	residuum and in carbonatite	Pe				Pokrovsky, 1995
REE	G	Araxa, Barreiro carbonatite	composite deposit	BR	Brazilian Shield, fringe of Parana Basin	REE min. disseminated in residual ochre and in carbonatite breccia	Cr	17.5 Mt	1.25 %	Nb,Th	Wooley, 1989
REE	G	Olympic Dam	deposit	AU-SA	Gawler Craton, Olympic Domain	bastnasite, monazite dissem. in hematitic breccia in granite	1,585	15 Mt	0-.2 %	Cu,U,Au,Ag,Fe	Ehrig et al. 2012
Sb	SG	Xikuangshan	cluster	CH	Yangtze Craton	stibnite replacements and veins in marble and schist	Cr	2.2 Mt	3 %	As	Wu Jiada et al., 1990
Sb	SG	Woxi mine	zone	CH	Yangtze Craton	set of stratabound qz, stibnite, scheelite horiz. in schist	Cr	1.67 Mt	2.5 %	W,Au,As	Gu et al., 2012
Sb	SG	Donlin Creek	cluster	US-AK	Kuskokwim region, Alaska	set of Au-quartz-stibnite-arsenopyrite fault & fissure veins	71-65	973 Kt	0.35 %	Au,As	Goldfarb et al. 2005
Sb	SG	Olimpiada	zone	RS	Siberian Platform, Yenisei Range	orogenic Au, disseminated sulfides in black schist // shear	794 615	900 Kt	0.2 %	Au,As	Goldfarb et al. 2005
Sb	SG	Murchison Range	zone	SA	Kaapvaal Craton Murchison greenst.belt	set of quartz-stibnite lodes in silicif.& sericitiz. shear in greenst	Ar	640 Kt	5 %	Au,Hg,As	Abbott et al., 1986
Sc	M	Tomtor complex	cluster	RS	Siberian Platform Udgy Paleorift	Nb,REE,Sc minerals in reworked residuum and in carbonatite	Np Pe	80 Kt	0.038 %	REE,Nb,Ta	Kravchenko & Pokrovsky, 1995
Sc	S	Zholtye Vody (Zhofti Vodi)	cluster	UK	Ukrainian Shield, Krivoi Rog belt	Sc in alkaline metasomatites under U oreb., in BIF near syenite	Pp	15 Kt	50-200 ppm	U,REE	Tarkhanov et al., 1991
Sc	S	Fifield-Owendale	deposit	AU-NW	Tasman orogenic system, Lachlan foldbelt	Sc enriched in lateritic profile over ultrabasics	T	3,434 t		PGE	Solomon et al., 1994
Se	L	Almalyk (Olmalyk)	cluster	UZ	Tian Shan orogen, Kurama Range	trace Se in porphyry Cu-Au-Mo in granod. & monzonite porphyry	314	13,230 t	2.3 ppm	Cu,Au,Mo,Ag	Yakubchuk et al., 2012
Se	M	Boliden	deposit	SW	Baltic Shield, Skellefte ore belt	trace Se in massive arsenopyrite body: VMS, hi-sulfidation hybrid	1,760	3,300 t	394 ppm	As,Au,Bi	Weihed et al., 1996
Sn	SG	Gejiu (Kochio)	district	CH-YN	Cathaysian orogen	5 clusters of cassiterite, pyrite, Cu,Zn,Pb replacements in marble	Cr	3 Mt	0.5-14 %	Cu,Pb,Zn,Ag	Pirajno, 2013
Sn	SG	Cornwall Sn placers	area	GB	Variscan orogen, Cornwall	alluvial and sea floor cassiterite placers; historical production	T3-Q	2.5 Mt			Jackson et al., 1989
Sn	G	Llallagua (Catavi)	cluster	BO	Andes, Cordillera Oriental of Bolivia	dissem. cassiterite with tourm. in subvolc.intrusion; veins	20.6	2 Mt	0.3-5 %		Ahlfeld & Schneider-Scherbina, 1964
Sn	G	Dachang	cluster	CH	Cathaysian orogen	complex Sn,Pb,Zn,Ag limestone replac., skarn, greisen near granite	91	1.5 Mt	1 %	Pb,Zn,Ag	Tanelli & Lattanzi, 1985
Sn	G	Kinta Valley (Ipoh)	district	ML	Western Range (granite belts)	extensive alluvial & residual placers over Tr tin granite complex	T3-Q	1.98 Mt			Schwartz & Askury, 1989
Ta	G	Ilimaussaq, Kringlerne deposit	deposit	GL	Gardar Rift province, southern Greenland	Ta is in eudialyte in kakortokite layers in agpaitic syenite	1,168	205,000 t	222 ppm	Zr,Nb	Nielsen, 1973
Ta	L	Ghurayyah, Midyan	deposit	SB	Arabian Shield, late anorogenic intrusions	Ta elevated content in stock of peralkaline riebeckite granite	Or	93,000 t	211 ppm	Zr,REE,Y,Nb Th,U	Drysdall et al., 1984

Ta	L	Lovozero layered intrusion	intrusion layers	RS	Baltic Shield, Kola, anorog. alkaline intrusions	Ta in loparite layers in agpaitic layered intrusion	370	80,000 t	500 ppm	Zr,REE,Nb	Kogarko, 1987
Ta	L	Motzfeldt, Igaliko intrusion	deposit	GL	Gardar Rift province, southern Greenland	Ta in pyrochlore disseminated in nepheline syenite	1,310	72,000 t	120 ppm	Zr,Nb	Tukiainen, 1988
Ta	L	Toongi (Dubbo project)	deposit	AU-NW	Lachlan foldbelt, anorog. basalt-trachyte assoc.	high trace Ta disseminated in subvolcanic trachyte plug	J	62,000 t	250 ppm	Zr,REE,Nb	Alkane NL website, 2002
Te	SG	Uchaly VMS	2 deposits set	RS	Urals orogen, Magnitogorsk Arc	trace Te in Cu,Zn VMS lenses in deformed bimodal metavolcanics	365 390	15,700 t	70 ppm	Cu,Zn,Ag,Au	Franklin et al., 2005
Te	SG	Gai (Gaiskoe) mines	cluster	RS	Urals orogen, Magnitogorsk Arc	race Te in Cu,Zn VMS lenses in deformed bimodal metavolcanics	376	12,000 t	26 ppm	Cu,Zn,Ag,Au	Franklin et al., 2005
Te	SG	Pueblo Viejo	cluster	DR	Greater Antillean island arc (Cr)	trace Te in submarine high-sulfidation Au-Ag system	115	11,000 t	20 ppm	Au,Ag,Zn,Se	Kesler et al., 2003
Te	SG	Jinding (Lanping)	cluster	CH	Lanping-Simao Basin	Te in disseminated Zn,Pb sulfides in sedim.rocks along thrust	130-110	9,700 t	44 ppm	Zn,Pb,Ag,Cd	Leach et al., 2005
Th	G	Araxa, Barreiro carbonatite	composite deposit	BR	Brazilian Shield, fringe of Parana Basin	Th enriched in pyrochlore dissem. in residual ochre & carbonatite	Cr	1.67 Mt	0.12 %	Nb,REE,U	Wooley, 1989
Th	L	Lemhi Pass	cluster	US-MT	Northern Rocky Mountains, Montana	Th in swarm of quartz & K-feldspar fault and fissure veins	T1	600 Kt		REE	Staatz et al., 1972
Th	L	Elliot Lake	district	CN-ON	Canadian Shield, Southern Province	Th in monazite & thorite in basal pyritic quartz conglomerate	2,350	350 Kt	0.07 %	U,REE,T	Roscoe, 1996
Th	L	Round Top Laccolith	intrusion	US-TX	Cordillera, Trans-Pecos region	trace & accessory Th minerals disseminated in alkal.rhyolite	36	320 Kt	200 ppm	REE,Be,Zr	Price et al., 1990
Th	L	Fen alkaline-carbonatite complex	cluster	NW	Caledonides orogen	Th minerals disseminated in hematitic carbonatite	Cm	132 Kt	0.2 %	Nb,REE	www.reeminerals.no, 2012
Ti	G	Bushveld complex magnetite layers	intrusion	SA	Kaapvaal Craton, Bushveld Complex	Ti in ilmenite and Ti-magnetite in Main Zone magnetitite layers	2,060	866 Mt	7.5 %	Fe,V	Cawthorn et al., 2005
Ti	L	Powderhorn complex	intrusion	US-CO	Colorado Rocky Mountains	Ti in perowskite disseminated in biotite pyroxenite	Cm	138 Mt	7 %	Nb	Temple and Grogan, 1965
Ti	L	Magpie Mountain	deposit	CN-QU	Canadian Shield, Grenville Province	steep wedge-like zone of massive Ti-magnetite in anorthosite	Mp	220 Mt	6.3%	Fe	Valleé & Raby, 1971
Ti	L	Nile Delta beach sands	coastal area	EG	Mediterranean coast of Egypt	Ti in ilmenite > leucoxene > rutile in heavy minerals fractionj	Q	108 Mt		Fe,Zr,REE	Said, 1962
Ti	L	Liganga massif	intrusion	TZ	Tanzania Craton	ilmenite & Ti-magnetite disseminated in anorthosite	Np	96 Mt	7.8 %	Fe	Harris, 1961
Ti	L	Dak Nong bauxite area	area	VI	Indosinian Plate cover	Residual accessory Ti component in gibbsitic lateritic bauxite	Q	61 Mt	2.28 %	Al,Fe	Bárdossy and Aleva, 2009
U	SG	Olympic Dam	deposit	AU-SA	Gawler Craton, Olympic Domain	U in uraninite & brannerite dissem. in hemat. breccia complex; IOCG	1,585	1.992 Mt	208 ppm	Cu,Au,Ag, REE	Ehrig et al. 2012
U	G	Billingen-Falbygden area, Kolm Shale	area	SW	Baltic Shield, Cm-Or platformic cover	high trace U in layer of bituminous shale	Cm2-3	993 Kt	292 ppm	Mo	Andersson et al., 1985
U	G	Chu-Sarysu Basin	basin	KZ	Chu-Sarysu Basin, Tian Shan Foreland	sandstone U infiltrations in Cr & Eo channel sandstone	Eo	960 Kt	250 ppm		www.uranium1.com

U	G	Elkon, Central Aldan	cluster	RS	Aldan Shield	U in alkaline metasomatites superimposed on shear zones	J	450 Kt	0.17 %	Au	Dahlkamp, 1993
U	G	Grants district	basin	US-NM	San Juan Basin	U in humate infiltrations in J sandstone	J	450 Kt	0.1 %	V	Dahlkamp, 1993
V	G	Athabasca Tar Sands V by-product	basin	CN-AB	North American Interior Plains	trace V in bitumen cement of tar sands-bedded sedimentary deposit	Cr	64 Mt	240 ppm	Zr,Ti	Johnson & McMillan, 1993
V	G	Bushveld Complex magnetite-P & Rv	intrusion	SA	Kaapvaal Craton, Bushveld Complex	V content in Main Zone magmatic magnetite layers		50 Mt	0.8 %	Fe,Ti	Cawthorn et al., 2005
V	G	Hongge	deposit	CH-YN	Emeishan Plume magmatic complex	V in Ti-magnetite magmatic layers		14.5 Mt	0.31 %	Fe,Ti	Pirajno, 2013
V	L	Kerch Fe ore field	sedimenta-ry layer	UK	Russian Platform cover	goethite & chlorites ironstone	J	11.4 Mt	0.67%	Fe,As	Sokolov & Grigor'ev, 1974
V	L	Bakchar	sedimenta-ry layer	RS	West Siberian Basin	trace V in bedded sedim. layers of hematite, siderite, leptochlorites	Cr3	3.64 Mt	0.13 %	Fe	Tomskaya Kompleksnaya Ekspedicia, 1964
V	L	Julia Creek	sedimenta-ry layer	AU-QU	Eromanga Basin	trace V in oil shale horizon	Cr1	3.78 Mt	0.21 %		Solomon et al., 1994
W	G	Xihuashan	deposit	CH-JX	Yangtze Craton margin	swarm of qz-wolframite veins in & above granite cupola	151-147	891 Kt	0.102 %	Sn,Bi	Pirajno, 2013
W	G	Verknye Kairakty (Qairaqty)	cluster	KZ	Kazakh-Mongol collage, Kipchak Arc	W,Mo,Bi veins & stockw. above granite cupola; regolith	Cb3	880 Kt	0.102 %	Mo,Bi	Russkikh & Shatov, 1996
W	G	Dahutang	cluster	CH	Yangtze Craton margin, Jiangnan Massifi	stockw. & dissem. wolgramite & scheelite in greiisen	139	880 Kt	0.152 %		Pirajno, 2013
W	G	Shizhouyuan	cluster	CH-HN	South China Block, Nanling Range	scheelite > wolframite.in greisen and skarn around granite stock	162-150	800 Kt	0.5 %	Sn,Mo,Bi,Be Pb,Zn	Lu et al., 2003
W	G	Sangdong	deposit	KO	Okcheon orogen, Taebaek Mts.	scheelite exoskarn in marble above granite cupola	Cr3	508 Kt	0.25 %	Mo	Kwak, 1987
Y	L	Tomtor	composite deposit	RS	Siberian Platform, Udgy Paleorift	Nb,REE,Sc,Y minerals in reworked residuum and in carbonatite	Np, Pe	1.2 Mt	0.3-0.8 %	Nb,REE,Ta, Sc	Kravchenko & Pokrovsky, 1995
Y	L	Ilimaussaq, Kringlerne deposit	deposit	GL	Gardar Rift province, southern Greenland	Y is in eudialyte in kakortokite layers in agpaitic syenite	1,168	790 Kt	0.08 %	Zr,REE,Ta	Nielsen, 1973
Y	L	Ghurayyah	deposit	SB	Arabian Shield, late anorogenic intrusions	Y elevated content in stock of peralkaline riebeckite granite	Np	583 Kt	0.13 %	Zr,REE,Ta, Nb,Th,U	Drysdall et al., 1984
Y	L	Ilimaussaq, Kvanefjeld	deposit	GL	Gardar Rift province, southern Greenland	Y in steenstrupine disseminated in lujavrite	Np	417 Kt	674 ppm	U	Nielsen, 1973
Y	L	Toongi (Dubbo project)	deposit	AU-NW	Lachlan foldbelt, anorog. basalt-trachyte assoc.	high trace Y disseminated in subvolcanic trachyte plug	J	274 Kt	0.11 %	Zr,REE,Ta, Nb	Alkane NL website, 2002
Zn	G	Howard's Pass (Summit Lake)	zone	CN-YU	Canadian Cordillera, Selwyn Basin	zone of very fine sedex Pb-Zn sulfides in silicified slate	S1	38.5 Mt	5 %	Pb,Ag	Leach et al., 2005
Zn	G	Mount Isa-Hilton zone	zone	AU-QU	Mount Isa Inlier West	N-S zone of stratabound Zn-Pb (sedex?) orebodies in dolom.slate	1,650	37 Mt	10 %	Pb,Ag,Cu	Large et al., 2005

Zn	G	Red Dog cluster	cluster	US-AK	Cordillera Alaska, Brooks Range	set of massive Zn,Pb sulphide & barite sedex in black shale	338	31 Mt	16.6 %	Pb,Ag	Leach et al., 2005
Zn	G	Upper Silesia (Krakow-Bytom) area	area	PL	Variscan orogen cover	5 MVT Zn>Pb sulfide clusters in dolomitized limestone	135	28 Mt	3.8 %	Pb,Cd	Leach et al., 2005
Zn	G	Broken Hill NSW	composite deposit	AU-NW	Curnamona Province, Broken Hill Domain	7 overlapping lenses of massive Pb,Zn sulfides in hi-grade gneiss	1,690	27 Mt	8.5 %	Pb,Ag,Cu Sb,As	Large et al., 2005
Zn	G	McArthur River, HYC deposit	deposit	AU-NT	Mount Isa Inlier McArthur Basin	set of siliceous layers in black shale with finely dissem.Pb-Zn sulf;sedex	1,638	20.88 Mt	9.2 %	Pb,Ag	Large et al., 2005
Zr	SG	Lovozero eudialyte layers	layered intrusion	RS	Baltic Shield, Kola D alkaline intrusions	Zr in eudialyte-rich layers in agpaitic syenites	370	210 Mt	1 %	Ti,Ta,Nb	Kogarko, 1987
Zr	G	Ilimaussaq eudialyte layers	layered intrusion	GL	Gardar Rift, Southern Greenland	Zr in eudialyte-rich layers in agpaitic syenites	1168 1020	38 Mt	1.1 %	Ti,Ta,Nb	Nielsen, 1973
Zr	L	WIM 150 deposit, Horsham	deposit	AU-VI	Murray Basin, Victoria	zircon and other heavy minerals in fine fossil beach/dune sands	T-Q	9.1 Mt	0.13 %	Ti,REE	Roy et al., 2000
Zr	L	Nile Delta beach sands	coastal area	EG	Mediterranean coast of Egypt	zircon and other heavy minerals in recent beach/dune sands	Q	8 Mt		Ti,REE	Said, 1962
Zr	L	Toongi (Dubbo project)	deposit	AU-NW	Lachlan foldbelt, anorog. basalt-trachyte assoc.	high trace Zr disseminated in subvolcanic trachyte plug	J	3.24 Mt	0.43 %	REE,Ta,Nb, Hf	Alkane NL website, 2002

NOTES: Please read Appendix for country codes; SG=super-giant; G=giant; L=large; M=medium; S=small deposit. Ages are in Ma or in abbreviations (Ar=Archean, Pp=Paleoproterozoic, Mp=Mesoproterozoic, Np=Neoproterozoic, PZ=Paleozoic, Cm=Cambrian, D=Devonian, Cb=Carboniferous, Pe=Permian, MZ=Mesozoic, Tr= Triassic, J=Jurassic, Cr=Cretaceous, T=Tertiary, Eo=Eocene, Ol=Oligocene, Q=Quaternary)

Table 3.3. Selected unconventional, mostly non-delineated metal accumulations and their estimated metals endowment

metal	resource	metal tonnage	grade	clarke ppm	concentra-tion factor	world production	supply years	reference
Ag	Georgina Basin phosphorites, Queensland Alum Shale, southern Sweden	5,700 t 11,480 t	1.5 ppm 1.4 ppm	0.07	21.43 20.00	33,800 t	0.17 0.36	Altschuler, 1980 Andersson et al. 1985
Al	Hekpoort basalt sericite-pyrite paleosol, SA Piceance Basin oil shale, accessory dawsonite One average anorthosite massif, 10x10x1 km	500 Bt 3.1 Bt 471 Mt	16 % 2.1 % 18.1 %	80,000	2 -2.625 2.26	32.25 Mt	15.5 96 14.6	Button, 1979 Smith & Milton, 1966 own calculation
As	Kerch Fe ore basin, trace As	2.2 Mt	<0.13 %	1.7	765	39,364 t	55.8	Sokolov & Grigor'ev, 1974
Au	Black shale intervals in some Au-vein districts	estimated ~1 Kt	0.1-1 ppm	0.00025	400-4,000	2,700 t	0.37	
Be	Round Top Batholith US-TX, trace Be in alkali rhyolite	92,800 t	58 ppm	2.4	24.2	240	367	Price, 2004
Co	East Pacific metalliferous clays Pacific floor Fe-Mn nodules (prospective parts) Hawaii-Johnston-Palmyra Pacific Mn crusts	10^8-10^9 t 1 Bt 1-2 Mt	0.02 % 0.05-2.5 %	24	8.33 417	96,000 t	unlimited 15,625 15.6	Field et al. 1983 Bezrukov et al. 1970 Hein et al. 2000
Cr	Regoliths (laterite, saprolite) on ultramafics Ultramafic massifs (peridotite, serpentinite)	10^7-10^8 t unlimited	0.3-0.5 % 0.2-0.3 %	130	~30.76 ~19.23	7.5 Mt	-- unlimited	
Cu	East Pacific metalliferous clays Pacific floor Fe-Mn nodules (prospective parts)	10^9-10^{10} t 1.9 Bt	0.11% 0.01-2.0 %	25	44 ~250	16.1 Mt	248	Field et al. 1983 Bezrukov et al. 1970
Fe	Rapid Creek, NWT, Canada West Siberian Basin ironstones	5.8 Bt 300 Bt	21.5 % ~25%	43,000	5 5.8	495 Mt	11.7 632	
Ga	Jamaica red muds from bauxite processing	1,500 t	65 ppm	15	4.3	55 t	27.3	Bárdossy 1982
Ge	Residue after burning British coals (1950s situation)	200 Kt-1 Mt	0.1+ %	1.4	714+	68 t	unlimited	Paone, 1970
Li	LiCl dissolved in sea water	almost unlimited	170 ppb	18	0.009	34 Kt	unlimited	Garrels et al. 1975
Mg	$MgCl_2$ dissolved in sea water Dead See, Mg in lake water solution Any dolomite deposit	unlimited 12 Bt almost unlimited	0.13% 9 %	19,500	0.067	433 Kt	unlimited 28,436 unlimited	Garrels et al. 1975 Bentor & Mart, 1984 this paper
Mn	East Pacific metalliferous clays Pacific floor Fe-Mn nodules (prospective parts)	10^{11}-10^{12} 71 Bt	5 % ~21.6 %	720	69.4	14 Mt	unlimited 14,286	Field et al. 1983 Bezrukov et al., 1970
Mo	Mo in Bazhenov black shale, RS Trace Mo in Phosphoria Fm., US ID+MT (estimated) Alum Shale, southern Sweden	20.52 Bt 21-70 Mt 2.214 Mt	285 ppm <820 ppm 270 ppm	1.1	25.9 745 245	250 Kt	~84 My total	Gavshin & Zakharov, 1996 U.S. Dept.of Interior, 1981 Andersson et al. 1985
Nb	Any carbonatite	10^7-10^8 t	0.2 %	19	105	63 Kt	long time	Gold, 1963
Ni	Trace Ni in Phosphoria Fm., US ID+MT (estimated) East Pacific metalliferous clays Pacific floor Fe-Mn nodules (prospective parts)	12-40 Mt 10^9-10^{10} t 2.3 Bt	900 ppm 0.1 % 0.1-2 %	55	16.4 18.2 18-364	1.8 Mt	~2.22 My total	U.S. Dept.of Interior, 1981 Field et al. 1983 Bezrukov et al. 1970
REE	Any carbonatite and agpaitic syenite-ijolite complex	10^7-10^8 t	0.1-0.2 %	150	6.7-19	130 Kt	long time	
Se	Trace Se in Phosphoria Fm., US ID+MT (estimated)	2-7 Mt	110 ppm	0.12	917	1,460 t	>1370	U.S. Dept.of Interior, 1981

Ta	Lovozero and similar alkaline intrusions	10^5-10^6 t	20-150 ppm	1.1	18-136	790 t	long time	
Te	Pacific floor Fe-Mn nodules	~50 Mt	~216 ppm	0.0005	432,000	150 t	333 Ky	Haynes et al. 1986
Th	Round Top Batholith US-TX, trace Th in alkali rhyolite	320 Kt	200 ppm	8.5	23.5	300 t?	>1067	Price, 2004
Ti	Lateritic bauxites on basalt or diabase, by-product; world Coal-associated and other clay(stones) sourced from alkaline parents	1.6-5.5 Bt 10^{10}-10^{11} t	3-5 % 3-5 %	4,000	7.5-12.5	2.94 Mt	>544	Bardossy & Aleva, 1990
U	U dissolved in sea water U in Bazhenov black shale, RS Trace U in Phosphoria Fm., US ID+MT (estimated) Trace U in Chattanooga Shale; US-TN U in Alum Shale, southern Sweden Florida and Georgia phosphorite province, USA Morocco phosphate province	4 Bt 6 Bt 3-10 Mt 6 Mt 1.7 Mt 7.16 Mt 2.4 (or 6?) Mt	3.3 ppb <104 ppm <<150 ppm 60 ppm 213 ppm 60-110 ppm 80 ppm	1.7	0.0019 61.2 88.2 35.3 125.3 35-65 47	50,772 t	222 to 341 Ky total	Bloch 1980 Gavshin & Zakharov, 1996 U.S. Dept.of Interior, 1981 Swanson, 1961 Andersson et al., 1985
V	V in Bazhenov black shale, RS Trace V in iron ore in Kerch Basin, UK Trace V in bitumen in Athabasca Tar Sand deposit, CN-AB Phosphoria Fm, US-ID, V in black shale at top of Meade Peak Member Julia Creek, Queensland Alum Shale, southern Sweden	7.3 Bt 11.4 Mt 64 Mt 150 Mt 3.78 Mt 5.576 Mt	0.1025 % <0.67 % 240 ppm 0.5 ppm 0.21 % 680 ppm	100	10.25 >67 2.4 50 21 6.8	60,000 t	125 Ky total	Gavshin & Zakharov, 1996 Sokolov & Grigor'ev, 1974 McKelvey et al., 1986 Andersson et al. 1985
Y	Phosphoria Formation, Idaho & Montana, USA	5-15 Mt	~150 ppm	24	6.25	7,031 t	>711	McKelvey et al., 1986
Zn	Zn in Bazhenov black shale, RS Trace Zn in Phosphoria Fm., US ID+MT (estimated) Pacific floor Fe-Mn nodules	30.24 Bt 450-1,500 Mt ~200 Mt	0.12 % 5,000 ppm 0.11 %	65	18.5 76.9 16.9	12.4 Mt	>2,580 total	Gavshin & Zakharov, 1996 U.S. Dept.of Interior, 1981 Haynes et al. 1986
Zr	Lovozero layered intrusion of agpaitic syenite (whole)	~360 Mt	0.355 %	200	17.5	1.41 Mt	255	Vlasov et al. 1959

Table 4.1. Incremental increase of metal concentration and accumulation in geological and industrial systems on the example of copper.

System	**Material**	**Cu concentration**	**incremental conc. factor**	**cumulative conc.factor**
geological	Cu Clarke (bulk continental crust)	25 ppm	0	0
	tholeiitic basalt	100-300 ppm	4-12	4-12 aver.8
	magmatic-hydrothermal fluid	~1,000 ppm	~5	~48
	hypogene porphyry-Cu	0.5%	~5	200
	enriched porphyry-Cu (chalcocite)	2.0%	4	800
industrial	chalcopyrite concentrate	30.0%	15	12,000
	smelter copper	98%	3.27	39,240
	electrolytic copper	99.9%	1.02	40,025

Table 4.2. From rocks to ores: incremental increase of selected ore metal budgets

metal	**Clarke ppm**	**rock/common trace metal content**	**CF**	**anomalous trace metal rocks**	**CF**	**near-economic metalliferous rocks**	**CF**	**metal source-related deposits**	**CF**
		ultramafic association							
Cr	130	peridotite, aver. 0.2% Cr	15.4	Great Dyke peridotite, <0.77 % Ct	59.2	Bird River Sill Cr dunite, 4.1% Cr	315.4	Great Dyke chromitite layers ~36.4% Cr	2800
Ni	55	komatiitic peridotite average 0.2% Ni	36.4	New Caledonia peridotite <0.3% Ni	54.5	Dumont Sill dunite, 0.34% Ni	61.8	New Caledonia Ni laterites, ~2.0% Ni	364
		mafics (basalt, gabbro)							
Cu	25	MORB, plateau, arc basalts average ~70 ppm Cu	2.8	Skaergaard ferrogabbro, 250-600 ppm Cu	10-24	Gorokgov Subsuite mafics, Volynia, 0.1-0.2% Cu	40-60	Keweenaw native Cu deposits, 1.2-2.4% Cu	400-960
		shale, black shale							
As	1,7	average shale, 14 ppm black shale, 30 ppm	8.2 17.6	As anomalous black shales ~155 ppm	91.2	some black shales in Ben-digo, Sukhoi Log ~0.5%	294	Obuasi quarz-arsenopy-rite-Au veins ~2.7%	15900
Mo	1.1	average black shale ~20 ppm	18.2	Bazhenov shale, 285 ppm	259	Alum Shale, 270 ppm	245	Huangjiawan, 5.5% Mo	50000
V	100	average black shale, 205 ppm	2.05	Bazhenov shale, 1015 ppm	10.15	Phosphoria V shale unit ~0.12%	120	NW Karatau slate, 0.23% V	230
U	1.7	average black shale 8.5 ppm	5	Chattanooga Shale, 60 ppm	35.3	Bazhenov shale, 104 ppm	61.2	Ranstad Mine, 292 ppm	171.8
		alkaline and carbonatite							
Nb	19	nepheline syenite ~200 ppm average carbonatite ~0.2%	10.5 105.3	Lovozero nepheline syenite, 696 ppm	36.6	Lovozero lujavrite ~0.25%	131.6	Lovozero loparite urtite, 0.2-0.4% Araxá carbonatite, ~1.1%	105-210 579
REE	150	nepheline syenite, 800 ppm	5.3 13.3			Ilimaussaq nepheline syenite,	24.5	Kvanefjeld lujavrite, 1.21%	80.7 66.7

		carbonatite, ~0.2%				3680 ppm		Araxá carbonatite, ~1%	
Zr	200	nepheline syenite ~1120 ppm	5.6	Lovozero nepheline syenite total, 0.355 Zr	17.7	Ilimaussaq kakortokite zone, 0.89%	44.5	Ilimaussaq eudialytite layers, 5.7%	285

NOTES : Continental crust clarkes are after Wedepohl (1995); CF=concentration factors related to clarke. Data are from Belevtsev, ed., 1974; Cornwall, 1951; Farmer, 2004; Gavshin and Zakharov, 1996; Large et al., 2011; Mao et al., 2002; Nielsen, 1973; Wager and Mitchell, 1951.

Table 5.1. Approximate years of discovery of selected significant metallic deposits

~3000 BC	Eastern Desert-Au, EG	1851	Cadia 1-Cu, AUNW	1891	Cripple Creek-Au,USCO
	Fenghuangshan, CH	1851	Meggen-Zn, GE	1892	Tsumeb-Pb, NM
~3000 BC	Kerman belt-Cu, IN	1852	Central District-Cu,USNM	1892	Highland Valley 1-Cu, CNBC
~2700 BC	Rio Tinto, Tharsis-Au, SP	1853	New Idria-Hg, USCA	1892	Sullivan-Pb, CNBC
Bronze Age	Bor, Majdanpek-Cu, SER	1850s	Ballarat-Au, AUVI	1892	Salsigne-Au, FR
~1100 BC	Linares-Ag,Pb, SP	1854	El Teniente 2-Cu,CL	1893	Rosebery-Pb, AUTS
>700 BC+	Lavrion-Ag,Pb, GR	1856	Sudbury 1-Ni, CNON	1893	West Rand-U, SA
~1 AD	Kolar, Hutti-Au, IA	1856	Reocin-Zn, SP	1894	Kalgoorlie-Au, AUWA
~100 AD	Jiaodong-Au, CH	1859	Comstock-Au, USNV	1894	Norseman-Au, AUWA
~100 AD	Cornwall-Sn, GB	1859	Rammelsberg 2-Pb, GE	1895	Sierriita-Cu, USAZ
>100 AD	Rosia Montana-Au, RO	1860	Antamina-Zn, PE	1895	Moanda-Mn, GO
~900 AD	Dexing-Cu, CH	1861	Lake Geroge-Sb, CNNB	1895	Climax 2-Mo, USCO
968 AD	Rammelsberg 1-Ag,Pb, GE	1861	Darasun-Au, RS	1896	Pine Point-Zn, CNNW
1150	Mansfeld-Cu, GE	1862	Cortez-Au, USNV	1896	Klondike-Au, CNYT
~1200	Upper Silesia-Pb, PL	1863	Bingham-Zn, USUT	1896	Caridad-Cu, MX
~1300	Trepca-Pb, KV	1864	Butte 1-Cu, USMT	1896	Bingham replac-Cu, USUT
1300s	Bleiberg-Pb, AS	1864	Los Bronces-Cu, CL	1896	Leonora-Au, AUWA
1490	Idrija-Hg, SV	1865	Morenci-Cu, USAZ	1897	St. Ives-Au, AUWA
>1500	Marmato-Au, CO	1865	White Pine-Cu, USMI	1897	Dalnegorsk-Pb, RS
~1500	Katanga-Cu, CG	1867	Ely-Cu, USNV	1897	Red Lake-Au, CNON
1500s	Zacatecas-Ag, MX	1868	Cerro Verde-Cu, PE	1897	Xikuangshan-Sb, CH
1500s	Ammeberg-Zn, SW	1868	Palabora-Cu, SA	1899	Kipushi-Zn, ZA
1500s	Cerro de Pasco-Ag, PE	1869	Tintic-Zn, USUT	1899	Bau-Sb, ML
1500s	Mankayan-Cu, PH	1869	Park City-Ag, USUT	1899	Orange Hill-Cu, USAK
1522	Pachuca-Ag, MX	1869	Antimony Line-Sb, SA	1899	Falconbridge-Ni, CNON
1536	Santa Barbara-Ag, MX	1870	Twin Buttes 1-Cu, USAZ	1900	Bushveld-Cr, SA
1545	Potosi-Ag, BO	1870	Carlin 1-USNV	1900	Agua Rica 1-Cu, AR
1546	Fresnillo-Ag	1871	Tyrone-Cu, USNM	1900	Glacier Peak-Cu, USWA
1548	Guanajuato-Ag, MX	1872	Globe Miami-Cu, USAZ	1901	Bushveld-Fe, SA
1555	San Martin-Ag, MX	1874	Leadville-Pb, USCO	1901	Keno Hill-Ag, CNYT
1568	Andacollo-Cu, CL	1874	Butte 2-Cu, USMT	1902	Fairbanks-Au, USAK
1600s	Chuquicamata-Cu, CL	1876	Homestake-Au, USSD	1902	Bor 2-Cu, SRB
1630	San Cristobal-Ag, BO	1877	Bisbee-Cu, USAZ	1903	Cobalt-Ag, CNON
1636	Keweenaw 1-Cu, USMI	1877	Hillgrove-Sb, AUNW	1903	Chambishi-Cu, ZA
1696	Kiruna-Fe, SW	1878	Waihi-Au, NZ	1904	Famatina 1-Mo, AR
1700s	Manto Verde-Cu, PE	1879	Climax 1-C, USCO	1904	Bingham Canyon-Cu, USUT
1700s	Toquepala-Cu, PE	1879	Chuquicamata 2-Cu, CL	1904	King Island-W, AUTS
1700s	Bangka placers-Sn, ID	1880	Tarkwa-Au, GH	1905	Quebrada Blanca 1-Cu, CL
1700s	Pima-Mission Cu-USAZ	1880	Rosemont-Cu, USAZ	1905	Santa Rita-Cu, USNM
1702	Ajo 1-Cu, USAZ	1880	Collahuasi-Cu, CL	1906	Dzhezkazgan 2-Cu, KZ
1706	El Teniente 1-Cu, CL	1881	Castle Dome-Cu, USAZ	1906	Touissit-Pb, MR
1720	La Motte-Pb, USMO	1882	Witwatersrand 1-Au, SA	1906	Round Mountain-Au, USNV

1725	Morro Velho-Au, BR	1882	Bagdad-Cu, USAZ	1907	Xihuashan-Sb, CH
1734	Morro do Ouro-Au,BR	1882	Mount Morgan-Au, AUQU	1907	Kidston-Au, AUQU
1749	Nezhdaninskoe-Au, RS	1882	Malanjkhand-Cu, IA	1908	Bushveld UG2-PNG, SA
1760	Dzhezkazgan 1-Cu, KZ	1882	Cadia 1-Cu, AUNW	1909	Dome-Au, CNON
1760	Cananea-Cu, MX	1883	Broken Hill-Pb, AUNW	1910	Outokumpu-Cu, FN
1763	Recsk Lahocza-Cu.HU	1883	Sudbury 2-Ni, CNON	1911	La Coipa-Ag, CL
1771	Hualgayoc-Au, PE	1883	Mount Lyell-Cu, AUTS	1911	Kerr Addison-Au, CNON
1784	Ridder-Sokolnoe-Pb,KZ	1883	Getchell 1-Au, USNV	1911	Kirkland Lake-Au, CNON
1793	Titiribi-Au, CO	1883	Pulacayo-Ag, BO	1913	San Rafael-Sn, PE
1801	Santa Rita-Cu,USNM	1884	Copper Mountain-Cu, CNBC	1913	Sibai-Cu, RS
1802	Weipa-Al, AUQU	1884	Coeur d'Alene-Ag, USID	1914	Los Pelambres 1-Cu, CL
1825	Dexing 2-Cu,CH	1884	Lena placers-Au, RS	1915	Kolyma placers-Au, RS
1830	Itabira-Fe, BR	1884	Frood Mine-Ni, CNON	1915	Donlin Cr.1-Au, USAK
1833	Pulacayo-Ag, BO	1885	Obuasi-Au, GH	1915	Ajo 2-Cu, USAZ
1838	Balmat-Pb, USNY	1886	Sukhoi Log 1-Au, RS	1915	Flin Flon-Cu, CNMB
1840	Sra Nevada foothills-Au,USCA	1886	Klerksdorp 1-Au, SA	1916	Potrerillos-Cu, CL
1842	Urucum-Fe, BR	1886	Malanjkhand 1-Cu, IA	1916	Sangdong-W, KO
1844	L.Superior-Fe, US	1886	Safford-Cu, USAZ	1917	Gibraltar-Cu, CNBC
1845	Keweenaw 2-Cu, USMI	1886	Central Rand-Au, SA	1917	Casino-Cu, CNYT
1846	Ray-Cu, USAZ	1888	East Rand-Au, SA	1917	Tintaya-Cu, PE
1848	Tri State-Zn,USOK	1888	Mount Magnet-Au, AUWA	1919	El Soldado-Cu, CL
1848	Mother Lode-Au,USCA	1888	Greenbushes-Sn, AUWA	1920s	Kilo-Au, CG
1851	Bendigo-Au, AUVI	1890	Renison Bell-Sn, AUTS	1920	Noril'sk-Ni, RS

1920	Panguna-Cu, PNG	1950s	Endako-Mo, CNBC	1965	Kambalda-Ni, AUWA
1921	Questa-Mo, USNM	1950s	Changpo Dachang-Sn, CH	1966	Uderei-Sb, RS
1921	Pechenga-Ni, RS	1950	Gai-Zn, RS	1966	Ann Mason-Cu, USNV
1921	Gaspé-Cu, CNQU	1950	Evander-Au, SA	1966	Kemess-Cu, CNBC
1922	Morobe-Au, PNG	1950	G. Fisher-Pb, AUQU	1966	Malanjkhand-Cu, IA
1923	Malartic-Au, CNQU	1950	Pima Mission 2-Cu, USAZ	1966	Imouraren-U, NR
1923	Nchanga-Cu, ZA	1950	Mountain Pass-REE, USCA	1966	Frieda River-Cu, PNG
1923	Mufulira-Cu, ZA	1950	Grants-U, USNM	1966	Yulong-Cu, CH
1923	Mount Isa-Pb, AUQL	1952	Mineral Park-Cu, USAZ	1967	Dukat-Ag, RS
1923	Noranda-Cu, CNQU	1952	Wellgreen-Ni, CNYT	1967	Elmwood-Zn, USTN
1924	Merensky-PGE, SA	1952	Hamersley-Fe, AUWA	1967	Island Copper-Cu, CNBC
1924	Konkola-Cu, ZA	1952,3	Brunswick #12-Pb, CNNB	1967	Stillwater-PGE, USMT
1924	Mount Isa-Pb, AUQU	1953	Elliot Lake-U, CNON	1967	Taca Taca-Cu, AR
1924	Boliden-As, SW	1954	Gamsberg-Zn, SA	1967	Carajás-Fe, BR
1925	Almalyk-Cu, UZ	1954	Mt. Pleasant-W, CNNB	1967	Los Pelambres 2-Cu, CL
1926	Khaidarkan-Hg, KS	1954	Malmbjerg-Mo, GL	1967	El Indio 1-Au, CL
1927	Bayan Obo-Fe, CH	1954	Mount Isa-Cu, AUQU	1967	Ertsberg 2-Cu, ID
1927	Balei-Au, RS	1955	Galore Creek-Cu, CNBC	1967	Rōssing 3-U, NM
1928	Kounrad-Cu, KZ	1955	Quellaveco-Cu, PE	1968	Waisoi-Cu, FJ
1929	Rōssing 1-U, NM	1955	Albazino-Au, RS	1968	Petaquilla-Cu, PA
1929	Toromocho-Cu, PE	1955	Butte porph-Cu, USMT	1968	Ok Tedi-Cu, PNG
1929	Berg-Mo, CNBC	1955	McArthur R.-Pb, CNNT	1968	Alumbrera-Cu, AR
1929	Red Chris-Cu, CNBC	1955	Araxá-Nb, BR	1968	Kholodnina-Pb, RS
1930	Bozshakol-Cu, KZ	1955	Thompson-Ni, CNMB	1968	Palabora-Cu, SA
1930	Aitik-Cu, SW	1955	Rōssing 2-U, NM	1968	Red Dog 1-Zn, USAK
1930s	Fish Lake 1-Cu, CNBC	1955	Weipa 2-Al, AUQU	1968	Kalamazoo-Cu, USAZ
1930s	Bestyube-Au, KZ	1955	Viburnum-Pb, USMO	1968	Rabbit Lake-U, CNSK
1930s	Marinduque-Cu, PH	1955	Ambrosia L.-U, USNM	1969	Poston Butte-Cu, USAZ
1930s	Toledo-Cu, PH	1955	Red Dog 1-Zn, USAK	1969	Ertsberg buried-Cu, ID
1930s	Teghout-Mo, AM	1956	Gorevskoe-Pb, RS	1969	La Granja-Cu, PE
1932	Pirquitas-Ag, AR	1956	Dabaoshan-Cu, CH	1969	Ranger-U, AUNT
1934	Tyrnyauz-W, RS	1956	Koktenkol'-Mo, KZ	1970s	Andacollo-Au, CL
1934	West Wits-Au, SA	1956	Mountain Pass-REE, USCA	1970s	Blackwater-Au, USNV
1934	Bayan Obo-REE, CH	1956	Waigeo-Ni, PNG	1970s	Sungun-Cu, IN
1934	Getchell 2-Au, USNV	1957	Shaft Creek-Cu, CNBC	1970s	Olimpiada 2-Au, RS
1935	Yellowknife-Au, CNNW	1957	Michiquillay-Cu, PE	1970s	Roşia Poieni-Cu, RO
1935	El Arco-Cu, MX	1957	Lubin-Cu, PL	1970s	Rico-Mo, USCO
1936	Taoxikeng-W, CH	1957	Shizhouyuan-W, CH	1970	Taurus-Mo, USAK
1936	Ertsberg 1-Cu, ID	1957	Exotica-Cu, CL	1970	Mt.Emmons-Mo, USCO
1936	Akchatau-W, KZ	1957	Mt.Whaleback-Fe, AUWA	1970	Navan-Zn, IR
1936	Kempirsai-Cr, KZ	1957	Suwalki-Ti, PL	1970	Cerro Colorado-Cu, PA
1936	Porgera-Au, PNG	1958	Windy Craggy-Cu, CNBC	1970	Cañariaco-Cu, PE
1936	Climax Lower-Mo, USCO	1958	Cantung-W, CNNW	1970	Hinoban-Cu, PH
1937	Gaspé 2-Cu, CNQU	1958	Dalnee-Cu, UZ	1970	Relincho-Cu, CL

1937	Cuajone-Cu, PE	1958	Muruntau 1-Au, UZ	1970	Rio Blanco 2-Cu, CL
1939	Uchaly-Cu, RS	1958	Tuwu-Cu, CH	1971	Spinifex Ridge-Mo, AUWA
1939	Welkom 1-Au, SA	1959	Sulphurets 1-Au, CNBC	1971	Coroccohuayco-Cu, PE
1939	Chibuluma-Cu, ZA	1959	Storie-Mo, CNBC	1971	Aggeneys-Zn, SA
1940s	Kuranakh-Au, RS	1959	Spor Mt.-Be, USUT	1971	Soroako-Ni, ID
1940s	Majdanpek 2-Cu, SER	1960s	Felbertal-W, AS	1972	Maiskoe-Au, RS
1941	Yerington-Cu, NV	1960s	Duobaoshan-Cu, CH	1972	Gibraltar 2-Cu, CNBC
1941	Kalahari-Mn, SA	1960s	Aitik 2-Cu, SW	1972	Howards Pass-Zn, CNYT
1942	Laisvall-Pb, SW	1960s	Radomiro Tomic-Cu, CL	1972	Récsk 2-Cu, HU
1942	Jamaica baux-Al, JA	1960	Molango-Mn, MX	1972	Gag Island-Ni, ID
1942	Klerksdorp Vaal-Au, SA	1960	Jinding-Pb, CH	1972	Telfer-Au, AUWA
1943	Porgera 1-Au, PNG	1960	El Salvador 2-Cu, CL	1973	Casa Grande-Cu, USAZ
1943	Natal'ka-Au, RS	1960	Safford-Cu, USAZ	1973	Superior East-Cu, USAZ
1943	Kachar-Fe, KZ	1961	Lumwana-Cu, ZA	1973	Jerritt Canyon-Au, USNV
1944	El Salvador 1-Cu, CL	1961	Sukhoi Log 1-Au, RS	1973	Jabiluka-U, AUNT
1944	Bakyrchik-Au, KZ	1961	Talnakh-Ni, RS	1974	Aynak-Cu, AF
1945	Verkh. Kairakty-W, KZ	1962	Highland Valley 2-Cu, CNBC	1974	Elura-Zn, AUNW
1946	Welkom 2-Au, SA	1962	Carlin-Au, USNV	1975	Olympic Dam-Cu, AUSA
1947	Hilton-Pb, AUQU	1962	Thompson Creek-Mo, USID	1975	El Indio 2-Au, CL
1947	Nezhdaninskoe-Au, RS	1962	Kokpataz-Au, UZ	1975	Red Dog 2-Zn, USAK
1948	Haib-Cu, NM	1962	Groote Eylandt-Mn, AUNT	1976	Asgat-Ozernoe-Ag, RS
1948	Sarbai-Fe, KZ	1962	Kidd Creek-Zn, CNON	1976	Skorpion-Zn, NM
1949	Udokan-Cu, RS	1963	Rosh Pinah-Pb, NM	1976	Itataia-U, BR
1949	Sokolovka-Fe, KZ	1963	Cerro Colorado-Cu, CL	1977	Salobo-Cu, BR
1949	Blind River-U, CNON	1964	Erdenet-Mo, MO	1977	Escondida 1-Cu, CL
1950s	Olimpiada 1-Au, RS	1964	Panguna-Cu, PNG	1977	Mocoa-Cu, CO
1950s	Monywa-Cu, BM	1964	San Jorge-Cu, MX	1977	Rampura Agucha-Zn, IA
1950s	Hukeng-W, CH	1965	Fish Lake-Cu, CNBC	1977	Corvo Neves-Cu, PT
1950s	Jiama-Pb, CH	1965	Vasilkovskoe-Au, KZ	1977	Quebrada Blanca-Cu, CL
1950s	Yandera-Cu, PNG	1965	Muruntau 2-Au, UZ	1978	Borska Reka-Cu, SRB

ACCEPTED MANUSCRIPT

1978	Kumtor-Au, KS	1991	Ministro Hales-Cu, CL	2007	Tapada-Cu, PE
1978	Far SE-Cu, PH	1991	Ujina-Cu, CL	2008	Anthony-Mo, AUQU
1978	Collahuasi 2-Cu, CL	1991	Ernest Henry-Cu, AUQU	2008	Kamoa-Cu, ZA
1978	McLaughlin-Au, USCA	1992	Cerro Negro-Au, AR	2008	Merlin-Mo AUQU
1979	Leimengou-Mo, CH	1992	Nurkazgan-Cu, KZ	2009	Detour-Au,CNQU
1979	Sisson Brook-W, CNNB	1992	Tampakan-Cu, PH	2010	Taryn-Sb, RS
1979	Wafi-Golpu 1-Au, PNG	1993	Turquoise Ridge-Au, USNV	2010	Drazhnoe-Au, RS
1979	Gold Quarry-Au, USNV	1993	Tasiast-Au, MU	2013	Kibali-Au, ZA
1979	Kelian-Au, ID	1993	Galeno-Cu, PE		
1979	Rosario-Cu, CL	1993	Fortuna-Cu, CL		
1980s	Uzel'ga-Zn, RS	1993	Tuwu Yandong 2-Cu, CH		
1980s	Regalito-Cu, CL	1994	Pogo-Au, USAK		
1980s	Chengmenshan-Cu, CH	1994	Beaver Brook-Sb, CNNF		
1983s	Loulo-Au, MI	1994	Carmen de la F.-Cu, CL		
1980	Boddington-Au, AUWA	1994	Reko Diq-Cu, PK		
1980	St.Ives 2-Au, AUWA	1994	Agua Rica 2-Cu, AR		
1980	Cerro Casale-Cu, CL	1994	Cadia 2-Au, AUNW		
1980	Hishikari-Au, JP	1994	Alemão-Cu, BR		
1980	Red Dog 2-Zn, USAK	1994	Voisey's Bay-Ni, CNNF		
1980	Snowfield-Au. CNBC	1995	Veladero-Au, AR		
1981	El Abra-Cu, CL	1995	Spence-Cu, CL		
1981	Admiral Bay-Zn, AUWA	1995	San Cristobal-Ag, BO		
1981	La Coipa 2-Ag, CL	1995	Hope Bay-Au, CNNT		
1981	La Escondida 2-Cu, CL	1995	Angostura-Au, CO		
1981	Zhaman Aibat-Cu, KZ	1995	Marmato 2-Au, CO		
1981	Zaldivar-Cu, CL	1995	Mirador 1-Cu, EC		
1982	Hemlo-Au, CNON	1995	Fyodorova Tundra-PGE, RS		
1982	Ladolam-Au, PNG	1995	Resolution-Cu, USAZ		
1982	Cigar Lake-U, CNSK	1996	Pierina-Au, PE		
1982	Abra-Pb, AUWA	1996	Oyu Tolgoi 1-Cu, MO		
1983	Esperanza-Cu, CL	1996	Gaby-Cu, CL		
1983	Yanacocha-Au, PE	1996	Yangshan-Au, CH		
1983	Porgera 2-Au, PNG	1998	Vizcachitas-Cu, CL		
1983	Hellyer-Zn, AUTS	1997	Sadiola-Au, MI		
1984	Twin Creek 2-Au, USNV	1998	Cadia 3-Au, AUNW		
1984	Donggou-Mo, CH	1998	Cristalino-Cu, BR		
1984	Refugio-Cu, CL	1998	Yandong-Cu, CH		
1984	Chimney Cr.-Au, USNV	1998	Panantza-Cu, EC		
1985	Cannington-Pb, AUQU	1998	Antapaccay 2-Cu, PE		
1986	Tomtor-Nb, RS	1998	Wabu Ridge-Au, ID		
1986	Valverde-Zn, SP	1999	San Carlos-Cu, EC		
1986	Donlin Cr.2-Au, USAK	1999	Chancas-Cu, PE		
1986	Goldstrike-Au, USNV	1999	Toki 1-Cu, CL		

1986	Candelaria-Cu, CL	1999	Esperanza 2-Cu, CL
1986	Cerro Casale 2-Cu, CL	2000s	Navidad-Ag, AR
1987	Plutonic-Au, AUWA	2000s	Furong-Bi, CH
1987	Kevitsa-PGE, FN	2000s	Gross-Au, RS
1987	Skaergaard-PGE, GL	2000s	Volspruit-PGE, SA
1987	Twin Creek 2-Au, USNV	2000s	Livengood 2-Au, USAK
1987	Morro do Ouro-Au, BR	2000s	Los Helados-Cu, CL
1988	Grasberg-Cu, ID	2000s	Rainy River-Au, CNON
1988	McArthur-U, CNSK	2000s	Courageous L.-Au, CNNW
1988	Sunrise Dam-Au, AUWA	2000s	Zuun Mod-Mo, MO
1988	Igarape Bahia-Cu, BR	2000s	Haquira East-Cu, PE
1989	Carlin-Mike-Au, USNV	2000s	Los Filos-Au, MX
1989	Kanowna Belle-Au, AUWA	2000	Mirador 2-Cu, EC
1989	Pebble 1-Cu, USAK	2000	Mina Justa-Cu, PE
1990s	Tantahuatay-Au, PE	2000	Boyongan-Cu, PH
1990s	La Quinua-Au, PE	2000	Minas Conga-Au, PE
1990s	Bystrinskoe-Cu, RS	2001	Oyu Tolgoi 2-Cu, MO
1990s	Kaleje-Cu, PL	2002	Fruta del Norte-Au, EC
1990s	Sulmierzyce-Cu, PL	2002	Alto Chicama-Cu, PE
1990s	Maoling-Au, CH	2002	Cortez Hills-Au, USNV
1990s	South Deep Mine-Au, SA	2003	Regalito-Cu, CL
1990	Sossego-Cu, BR	2003	Prominent Hill-Cu, AUSA
1990	Batu Hijau-Cu, ID	2004	Eleanore-Au, CNQU
1990	Wafi-Golpu 2-Au, PNG	2005	Pebble 2-Cu, USAK
1990	Rosebel-Au, SU	2005	Tropicana-Au, AUWA
1990	Century-Zn, AUQU	2005	Frontera (Pelambres)-Cu, CL
1991	Pipeline-Au, USNV	2005	Spinifex Ridge 2-Mo, AUWA
1991	Magistral-Mo, PE	2006	Carrapateena-Cu, AUSA
1991	Minas Conga-Cu, PE	2006	La Colosa-Au, CO
1991	Cerro Vanguardia-Au, AR	2007	Caspiche-Au, CL
1991	Magellan-Pb, AUWA	2007	Toki 2-Cu, CL

Table 5.2. Numbers of giant and some world class deposits discovered since 1950, arranged by countries

No.	country	No.	country	No.	country
45	US United States	4	MO Mongolia	1	FJ Fiji
38	CL Chile	4	PH Philippines	1	FN Finland
33	AU Australia	4	PL Poland	1	HU Hungary
32	CN Canada	4	UZ Uzbekistan	1	IN Iran
19	RS Russia	3	MX Mexico	1	IR Ireland
19	PE Peru	3	VE Venezuela	1	JP Japan
18	CH China	3	ZA Zambia	1	KS Kyrgyzstan
9	PNG Papua New Guinea	2	GL Greenland	1	MU Mauritania
9	BR Brazil	2	IA India	1	NR Niger
8	ID Indonesia	2	MI Mali	1	PT Portugal
7	AR Argentina	2	PA Panama	1	RO Romania
6	SA South Africa	2	PK Pakistan	1	SP Spain
5	EC Ecuador	1	AF Afghanistan	1	SU Suriname
4	CO Colombia	1	AS Austria	1	SW Sweden
4	KZ Kazakhstan	1	BM Burma	1	SRB Serbia
4	NM Namibia	1	BO Bolivia		

Table 7.1. Selected examples of significant metallic deposits not mined for more than 20 years after discovery

Country	Deposit	Found	Available resource[1]	Reason for not mining
Afghanistan	Aynak-Cu	1974	12.3 Mt Cu	Prolonged lack of public security, government bureaucracy
Australia	Jabiluka-U	1973	207 Kt U	Originally shelved by "3 Mines Policy", now Aboriginal land dispute
	Admiral Bay-Zn,Pb	1981	7.7 Mt Zn	Too deep so presently uneconomic
	Abra-Pb	1982	3.74 Mt Pb	Too deep, not yet ready, exploration continues
	Spinifex Ridge-Mo	1971	496 Kt Mo	Blind deposit, presently uneconomic
Bolivia	Salar de Uyuni-Li	1800s,2000s	8.2 Mt Li	Government indecision, resources nationalism
	Cerro Rico, Potosi-Ag	1545	~70 Kt Ag	Partly mined, bulk mining would damage national symbol
Canada	Windy Craggy-Cu,Au	1958	4.1 Mt Cu	Environmental objections-save the wilderness
	Casino, Yukon-Cu,Mo	1917	4.5 Mt Cu	Low grade, poor access, environmental problems
	Hudson Bay Mt.-Mo	1960s	164 Kt Mo	Orebody under picturesque glacier, unsightly mining would damage
	Howards Pass-Zn.Pb	1972	38.5 Mt Zn	Access & processing problem (too fine-grained)
Chile	Cerro Casale-Au,Cu	1980	900 t Au	Difficult access, mining/processing problems, environmental
Czech Rep.	Mokrsko-Čelina, Au	1970s	~100 t Au	Public protest against mining: "Chekhia above gold"
	Hamr-Stráž, U	1960s	~100 Kt U	Devastation of drinking water aquifer by solution mining
Fiji	Waisoi (Namosi)-Cu	1968	7.4 Mt Cu	Limited interest (lack of mining supports), environmental
Germany	Ronneburg-U	1960s	~100 Kt U	Public opposition to uranium mining & processing
Greenland	Malmbjerg-Mo	1954	271 Kt Mo	No infrastructure (hence costly operations), environmental
	Skaergaard-PGE	1987	989 t PGE	No infrastructure (hence costly operations), environmental
	Ilimaussaq-REE,Ta	1960s	220 Kt Ta	Costly access, no infrastructure, environmental problems
Hungary	Récsk porphyry Cu	1972	10.2 Mt Cu	Deeply buried deposit, environmental problems if mined
Kazakhstan	Verkhnye Qairaqty-W	1945	900 Kt W	Lack of funding after USSR disintegration
Papua N.G.	Panguna-Cu,Au	1920,1964	~5 Mt Cu	Unsettled security-was behind Bougainville secession
	Frieda River-Cu	1966	6.73 Mt Cu	Difficult access, lack of mining support, security
Peru	Tía Maria-Tapada, Cu	1980s	3.04 Mt Cu	Public protest, mining might damage environment (agriculture) in valley
	Michiquillay-Cu	1957	4.55 Mt Cu	Lack of interest for long, now local environmental protests
Romania	Roşia Montană-Au	<AD 100	501 t Au	Public protest, village would have to be relocated
Russia	Udokan-Cu	1949	19.45 Mt Cu	Bypassed by Soviet central planning, now capital sought
	Sukhoi Log-Au	1886,1961	2,956 t Au	Bypassed by Soviet central planning, now capital sought
Sweden	Ranstad, Alum Shale	1800s	300 Kt U	Briefly mined, then closed by public protest against U mining
Tajikistan	Kanimansur-Ag,Pb	1950s	49 Kt Ag	Bypassed by Soviet planning, low grade, needs large investment
USA	Mt.Emmons-Mo	1970	372 Kt Mo	Local public protest; mining would downgrade ski area
	NE Duluth-Ni,Cu	1960s	29 Mt Cu	Exploration completed, environmental objection to mining
	Sierra Foothills, CA-Au	1840	~100 t Au	Mining of remnant Au gravels conserved to prevent pollution
	Thompson Creek-Mo	1962	324 Kt Mo	Access and environmental problems, Mo overproduction

1) Original metal tonnage or metal left after earlier mining

Table 7.2. Depletion of selected mineral deposit types with increasing depth of exploration and mining

Depth, m	**Ore type**	**estimated % lost**	**global depletion**
10 m sea floor	Fe-Mn nodules on the sea floor (eroded or lost to subduction)	~95%	N/A
100 m land	Gossans (with residual gold)	~90%	<0.1%
	Alluvial and beach placers (Au, Sn, heavy minerals)	~80+ %	Au ~3%
	Lateritic bauxite, Ni-laterite Playa brines for lithium, boron Supergene enriched Fe ore over banded iron formations Calcrete uranium Oxidation zones on Cu and other deposits, exotic deposits Hot spring gold deposits (erosion may expose epithermal roots)	~80+ % ~95+ % ~60 % ~90 % ~80 % ~70 %	Ni ~50% Al ~70% Li ~80% Fe ~20% U <1 % Cu <1 % Au <0.01 %
500 m	Presently exposed epithermal deposits (Au, Ag, Hg, Pb) Supergene enriched (chalcocite) zones over porphyry Cu Infiltrational (sandstone) uranium deposits Unconformity uranium deposits Mississippi Valley-type Zn-Pb deposits	~30-40 % >80 % ~60-70% ~40-50% ~60-70%	Au <2 % <20 % 20-30% ~30-40% Zn ~20%
1000 m	Porphyry Cu, Au, Mo-deposits (not supergene enriched) Epithermal deposits (Au, Ag, Pb-Zn, Cu) Volcanic-associated massive sulfides (VMC)	~20-30% ~60-70% no loss	~15-20% Au <3-5% N/A
5000 m	Porphyry deposits (Cu,Au,Mo) “Mesothermal“ base metals veins and replacements (Pb,Zn,Cu) Orogenic gold deposits in metamorphics	>95% ~70-80% ~10-20%	~60-80% Pb >30% Au <5%

ACCEPTED MANUSCRIPT