

Metals, Economy, and Exploration

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Say's Law states that "Production creates demand". The power for all people from across the socioeconomic spectrum to purchase what they need and want is created by production, not by mere "job creation". That is, the more productive we all are in our own jobs, the greater our ability to purchase the production of others. Innovations large and small, including those that result in Schumpeter's creative destruction, result in higher productivity, well-being creation, and economic growth. The well-being of the Earth's population is closely determined by this free generation of wealth and by the free exchange of goods and services in the world's markets, as implied by Say's Law.

The increase in well-being is driven by the quest for profit, by people acting in their own self-interest, and is tracked by the increase in world Gross National Income (GNI, which is close to world GDP). Many tangible goods, such as smart phones, cars, e-readers, tablets, our homes, as well as machinery for manufacturing, require metals for their production. Copper, present in wires, pipes and many other components too numerous to name, is critical for our economic well-being.

The demand for copper by the world populace generally increases, with about 3% more copper is demanded every year; only about 30% of world demand is met by recycling. Yet, the average price of copper, in constant dollars, has not risen substantially in a century. Overly simplistic depletionist, or "fixed stock" thinking would tell us that as old mines are closed, and companies explore for harder to find ores, the price should rise: but this is not what we find. Why? The answer is human innovation. Innovation occurs everywhere along the chain, from exploring for ore deposits, to the formation of companies, to the development of mineral prospects, to the mining and processing of the ore, to the marketing of the product metals, and indeed, to the final products of manufacturing. The shale oil and shale gas revolution expose the fallacies of Malthusian depletionist strategies.

Our research in the Laboratory for Mineral Deposits Research¹ in the Department of Geology of the University of Maryland, has, as its ultimate aim, the development of a better understanding of how ore deposits form. We study how some deposits of copper, molybdenum, gold, tungsten, silver, and more recently, rhenium, indium, zinc and other metals, are formed in the Earth's crust. Understanding the geological mechanisms by which metals are transported from large regions of the Earth's crust, where they are present in trace concentrations, to much smaller regions of the crust, where they are present in quantities (i.e., grades and tonnages) that can be mined at a profit, helps to inform explorationists as to how to better find new ore deposits.

A class of ores, known as porphyry copper-gold-molybdenum deposits, form as part of the present and past volcanic belts that are found around the world; these zones of volcanic activity are known as "volcanic arcs". The associated porphyry-type ore deposits are defined by successive envelopes of hydrothermal alteration typically enclosing a core of ore minerals disseminated in a "stockwork" - an interconnected network of small fractures and veins that are filled with quartz and copper-bearing

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minerals such as bornite and chalcopyrite. Porphyry ore bodies typically contain between 0.4 and 1 % copper with smaller amounts of other metals such as molybdenum, silver and gold.

Current models for the formation of porphyry ores suggest that they form above chambers of crystallizing molten rock (magma), a few thousand feet beneath volcanoes. As the magma cools, ultimately crystallizing granite and related rocks, gases comprising water plus salts, and possibly salt-rich liquids (brine), are released from the crystallizing magma, and bubble toward the top of the subterranean chamber of magma. Our experiments have shown that copper and other metals preferentially partition into the exsolving bubbles from the silicate melt.

Heat is constantly being lost from the magma to the relatively cold, surrounding rocks (the “country rocks”), and therefore crystals grow irreversibly from the magma as bubbles of gas, and possibly brine, form. The upward-directed buoyancy force applied to the relatively brittle, older, and colder overlying country rocks by the bubble-charged magma causes the country rocks to fracture. As the fractures form, the differing viscosities and surface tensions of the magmatic gas, compared to the molten rock, results in the preferential movement of the gas, (\pm salt-rich liquid) into small fractures at the expense of the crystallizing and thickening magma. According to our studies, copper partitions strongly into the chloride-bearing gases that bubble out of the hot magmatic soup. The presence of H₂S gas (the gas responsible for “rotten egg odor”), will enhance the concentration of copper in this highly fluid gas phase. The magmatic brine, if present, is always more enriched in copper than is the magmatic gas, according to all the conditions we have thus far examined. However, our laboratory experiments, together with our ideas about how we think magma-hot water distillation systems operate in the Earth, suggest that significant quantities of copper are transported away from the magma by phases that are quite gas-like in their physical behavior. Our results suggest that when both chlorides and H₂S are present together in sufficient amounts, they cooperate in transporting copper in chloro-sulfo-Cu complexes that enhance the copper concentration in the gas phase over what would be present with only chloride or sulfur (H₂S) alone: ***This is a surprising result, and shows why experiments of the type we perform are critical.*** At least for chloride-dominated gases \pm brines, the optimum pressure for copper partitioning into the volatile phases seems to be on the order of 100 MPa. These water-, chloride-, sulfur-, and metal-bearing magmatic gases and brines move through a network of upward branching fractures, and into cooler environs where they can chemically react with country rock, cool, and mix with other subterranean waters. The changing temperatures and pressures can permit the gases to condense more brine, and hence, determining whether coexisting brines found in ore zones were derived from primary magmatic brines can be challenging.

Many crystals of quartz and other minerals in ore deposits can contain small voids (some smaller than the diameter of human hair) filled with samples of the ancient waters that carried the ore substances to the veins and stockworks. Referred to as primary fluid inclusions, these microscopic drops of liquid, gas, and even microcrystals, can contain high concentrations of copper, even though they possess little in the way of chloride. Our experiments suggest that these liquids and gases are modified, or “evolved” magmatic fluids, as are essentially all “ore-forming fluids” derived from magmas.

Our experiments suggest a number of potential exploration tools that can be used to explore for even more deposits of copper (and related metals):

1. The inferred mass ratio of chloride to water in associated magmatic systems can be a critical parameter in exploration for porphyry-type deposits. The presence of primary brine fluid inclusions in vein quartz can be indicative of the high chlorinity of the magmatic-hydrothermal system. The presence of high ratios of Cl to H₂O in volcanic melt inclusions, or high Cl to OH in magmatic apatite, can also prove to be useful prospecting tools.

2. Whereas sulfur is also an essential constituent of the ore-related magmas and their evolving gases and liquids, magmas that are saturated with, and fractionate, sulfide minerals during their evolution, will yield a lower proportion of their ore metal (Cu) inventory to proto-ore fluids. Magmas that are highly oxidized through a large extent of their evolution should be more prospective to copper, and in some cases, gold.
3. Carbon dioxide, although common in magmatic gases, reduces the efficiency with which copper can be removed from magmas into potential ore fluids: those stages of magmatic development that are characterized by lower concentrations of carbon dioxide will have a higher probability of forming porphyry ore.