Minerals and Plate Tectonics (II): Seawater and Ore Formation

After decades of government control and stability, the price of gold has in the past few years gone up dramatically. The higher prices have stimulated new interest in gold exploration. As it happens, research into the geochemical processes by which ores are formed has also led to new interest in gold deposits among economic geologists and to new theories of their origins. The combination promises to revolutionize gold mining.

What is happening in gold is in many ways characteristic of the rethinking going on in many aspects of ore geology and geochemistry (*Science*, 5 September, 1975, p. 779). Oceanographic studies, heat flow measurements, drilling cores, and a host of geochemical studies have provided evidence that the oceans interact with the earth's crust on a far more massive scale than previously supposed. This interaction, several investigators have proposed, is fundamental to the plate tectonic process and to the global cycling of volatiles and other elements, including metals, through the crust. Specifically, attention has been focused on seawater's role in extracting metals from cooling volcanic rock and the enhanced concentrations that result.

One important class of gold ores is now thought by some geologists to have originally been deposited as sediments on the sea floor by just such a process. Known as lode gold deposits, they are typically mined from quartz veins or lodes and, apart from the huge placer deposits in South Africa, are the most significant source of this precious metal. The richest ores are found in belts of ancient greenstone and schist rocks and include such mines as Kalgoorlie in Western Australia, Morro Velho in Brazil, the Ontario districts of Porcupine and Kirkland Lake in Canada, and the Homestake mine in South Dakota. Smaller but geologically similar deposits such as the Mother Lode in California occur in younger rocks.

If the new proposals are correct, gold was leached from newly formed volcanic rocks on the sea floor by seawater. The gold then was deposited along with some distinctive iron minerals as sea floor sediments and covered with more volcanic rocks. These rocks are of the type associated with island arcs, although whether that interpretation is correct for the older, Precambrian rocks is still open to question, and they often contain copper, lead, and zinc deposits as well. According to Richard W. Hutchinson of the University of Western Ontario in London, Ontario, the gold appears to be distributed rather evenly and at low concentrations throughout a layer of primitive volcanic rocks found toward the bottom of a volcanic pile. A variety of sediments and other geochemical indicators attest to the fact that the gold-bearing layer was formed in a submarine environment.

The veins or lodes themselves in many instances are now thought to have been formed as the gold-bearing volcanic rocks were later deformed and reheated; fractures were then filled with quartz or other materials and gold from the surrounding rocks. In this view the veins are artifacts of the geologic history of the gold deposits subsequent to their formation; the gold was

The New Metallogeny: Impact on Exploration

One of the more striking instances of successful mineral exploration based on geological principles was the discovery, in the late 1950's, of the Kidd Creek Mine near Timmons, Ontario. Drilling into an innocuous outcrop of rhyolitic volcanic rock disclosed one of the largest ore deposits of its kind, over 200 million tons of ore that is 10.5 percent zinc and 2.5 percent copper. Canadian production of silver, which is also present in the ore in trace amounts, doubled the first year Kidd Creek went into operation. According to Leo Miller of Texas Gulf, to whom the discovery is credited, he had been impressed with reports of the volcanic origin of massive sulfide ore deposits (a new idea at the time) in the Japanese literature. He noted similarities between the geological settings of Japanese and much more ancient Canadian ore deposits and the fact that nearly 85 percent of these deposits occurred in rhyolitic rocks, and committed his company to an ultimately successful exploration program.

It might be supposed that bold programs such as that which found Kidd Creek are regular fare for mining companies, but the evidence is to the contrary. Indeed, many mineral companies have traditionally preferred to rely on "hunt and scratch" methods of exploration, on buying up the finds of independent prospectors, or on simple airborne geophysical surveys rather than undertake geological studies of a region. Not only are mining companies as a group marginally receptive (some academic geologists would say reactionary) in their attitude toward new geological ideas, a few have been known to regard geologists themselves as excess baggage on mine staffs. One apparently true anecdote to this effect concerns a mine in Brazil that hired its first geologist when it had only 6 months of ore left.

Calls to the chief geologists of a number of U.S. mining companies regarding the usefulness of new models of ore genesis arising from plate tectonics produced a largely skeptical response. While pronouncing the new concepts interesting and possibly useful for resource analysis, most of those contacted doubted their utility for exploration. Typical of this attitude were the comments of one chief geologist that the new ideas "do not help to spot a drill hole" and "are pretty much of a 'so what'?" as far as exploration is concerned.

Not all exploration groups are so skeptical of plate tectonics, however. The oil industry has enthusiastically embraced the new concepts as they relate to the basins and sedimentary formations where oil and gas are believed to occur and, as one oil company geologist put it, "would never go back to the old way of doing things." Oil companies appear to be moving into mineral exploration as well. Not surprisingly, they are what one academic observer described as "more enlightened" regarding new ideas of ore formation and more willing to fund research along these lines. According to James Mancuso of Exxon's mineral exploration group in Denver, Colorado, he would not hesitate to use plate tectonics concepts in presentations of exploration plans to management. Studies of regional geology and attention to new sources of information such as plate tectonic models and satellite photos now characterize their exploration programs, Mancuso says.

concentrated into the veins by water circulating through the rock, repeating the process that occurred when the original ore was laid down. Hence the veins, the exclusive focus of mining up to the present, are thought to be a secondary feature of much larger, low-grade deposits. Because of higher gold prices, it may be possible to mine the low-grade ores using open pit or other high volume techniques, as is now done for certain copper ores, thus recovering all of the gold. Several mining companies, especially in Canada, are reported considering such an approach (see box).

Other metal deposits appear to have undergone complex evolutions similar to that of gold. According to Bryan Fryer of the University of Western Ontario, seawater leaching of volcanic rocks and sediments may be important in forming initial concentrations of tin, tungsten, molybdenum, and silver, even though subsequent processes may determine where and in what form ore deposits actually occur. What seems to be emerging is recognition that it is easier to concentrate metallic ores in seawater than, as was long believed, in molten rock, although the presence of volcanism is presumed to be essential as a source of heat and, ultimately, of the metals themselves.

One model of the process is that proposed by John B. Corliss of Oregon State University. He suggests that seawater penetrates cracks in newly formed submarine volcanic rocks, setting up an extensive hydrothermal circulation driven by heat from the cooling rocks. Seawater interacts with the rocks, changing them chemically and releasing the metals. Chlorine from the seawater aids in leaching the metals by forming soluble metal-chloride complexes. The seawater then transports the metals up to the sea floor, where under appropriate circumstances they are precipitated to form metal-rich sediments. The hydrothermal circulation may penetrate deep into the volcanic material, perhaps 10 kilometers, extracting metals and altering the mineral composition of the rocks.

Similar suggestions have been made by William S. Fyfe of the University of Western Ontario and E. T. C. Spooner of Oxford. Fyfe, for example, points out that seawater supplies not only the chloride to help dissolve the metals but also sulfur (in the form of sulfates) and carbon dioxide, which become fixed in the upper layer of the ocean floor. As the brines return to the sea floor, sulfate helps to precipitate the metals.

Economic geologists have long known that metals are present in trace concentrations in a variety of volcanic rocks, but there has been and still is debate as to how they are concentrated to form ore deposits. There is evidence to suggest that hydrothermal circulations may indeed be the concentrating mechanism in many instances. Submarine volcanism occurs primarily at the mid-ocean ridges where new oceanic crust is formed and at island arcs above subduction zones. Oceanographers have noted that the conducted heat flow above mid-ocean ridges is often anomalously low, in agreement with the idea that much of the heat is convected away by hydrothermal circulation. Rocks dredged from the flanks of ridges show evidence of chemical alteration consistent with the hypothesis, and, according to preliminary results, so do cores obtained near the Mid-Atlantic Ridge last summer by the Deep Sea Drilling Project.

Several examples of active hydrothermal systems on the sea floor are known. The Red Sea, a center of incipient sea floor spreading, is perhaps the most studied of these. Since 1966 at least three U.S. expeditions and one West German team have visited the area. According to David A. Ross of Woods Hole Ocean-

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Is Slow, but Some See Good Prospects

University scientists are still more optimistic about the ultimate potential of plate tectonic concepts for exploration. Richard Hutchinson of the University of Western Ontario believes that the new ideas help in broad scale reconnaissance to define favorable regions. He cites exploration for gold and copper in the South Pacific islands such as that which led to the discovery of important copper deposits near Bougainville, New Guinea. Exploration has apparently proceeded by conventional methods but was inspired primarily by plate tectonic ideas. More specific applications have also occurred. Analogies with Cyprus and its ore-bearing ophiolite rocks, based on models of metal origins, have led to new exploration in Turkey and northern Iran; according to Hutchinson, ophiolites had been largely neglected in the search for ores until their identification as pieces of oceanic crust.

In some areas, such as Newfoundland and the Canadian Appalachians, plate-metallogenic models have reportedly been used in recent years to plan exploration programs in some detail. According to David Strong of Memorial University, St. John's, Newfoundland, the main advantage of the models is that they suggest where to look and where not to, thus reducing the area to be covered. Appreciation of a common plate tectonic origin for the entire Appalachian chain, for example, has led to a search for lead-zinc deposits in Newfoundland similar to those found in Tennessee. And Strong suggests that ultramafic rocks in the U.S. Appalachians, which are largely unexplored, may contain asbestos and chromium ore as do corresponding rocks in Canada. He himself reports being deluged with consulting offers from mining companies operating in Newfoundland—certainly one measure of the practical importance of the new theoretical knowledge.

Geochemical ideas about how ores are formed are also having practical applications. Evidence of hydrothermal brines associated with ore formation is being used in old mining districts in Canada to trace stratigraphic horizons over long distances. According to Bryan Fryer of the University of Western Ontario, the result has been the discovery of new massive sulfide metal deposits within sight of old mine shafts. In effect, Fryer says, what is beginning is exploration by stratigraphy, using naturally occurring geochemical markers, and by other classical geological techniques, a relatively new approach in ancient Precambrian rocks.

R. Ridler of the Geological Survey of Canada also reports that some companies are drilling exploratory holes on the basis of stratigraphic evidence. He believes that such techniques will find increasing use in gold exploration too, and that most gold mines in the future will exploit massive low grade ores rather than just the richer vein deposits (see accompanying article). Other observers confirm that several mining companies are developing exploration plans for gold that are designed to look for large low-grade deposits.

Almost certainly, the major impact of plate tectonic ideas and subsequent models of ore formation on mineral exploration is still to come. By all signs, however, a few of the more aggressive mining companies are not waiting for the future to come to them.—A.L.H.

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ographic Institution, brines as hot as 60°C were sampled near the sea floor. The circulation pattern seems to be downflow on the flanks, which are marked by thick salt deposits, and upflow near the center of the rift zone. The sediments on the sea floor, especially in one of several closed basins that are thought to promote precipitation, were enriched in copper, lead, and zinc to depths of 50 meters. The amount of metals present testifies to the effectiveness of the leaching process—on the 50-square-mile floor of the Atlantis II deep, for example, lie an estimated 3 million tons of zinc, 1 million tons of copper, nearly that much lead, and perhaps 5000 tons of silver, worth in all about $2 billion. Saudi Arabia and the Sudan, which border the Red Sea, have signed an agreement to share the sea floor resources, and an investigation of ways to process the ore is reported to be under way.

The closed basins and extremely high salinity of the Red Sea hydrothermal circulation make it something of a unique resource. The salinity in the open ocean, for example, could not build up as it has in the Red Sea basins; metal-bearing brines would also tend to be diluted and dispersed more once they reach the ocean. But investigators believe that similar processes do occur on the sea floor. French scientists last summer observed what they believe was a temporarily inactive hydrothermal system in dives along the Mid-Atlantic Ridge, and several research vessels have recently reported evidence of an active hydrothermal system in the Galápagos rift, a sea floor spreading center in the Pacific. Plans are under way to investigate the Galápagos site more carefully, including descending to the rift zone in submersibles to sample the fluids emerging from the sea floor and analyze their mineral content.

Other evidence of past hydrothermal systems comes from the polymetallic, massive sulfide ore deposits in ancient volcanic belts in Canada. According to R. H. Ridler of the Geological Survey of Canada, it is possible to distinguish a class of brine sediments, which he calls exhalites, associated with these ore deposits. These sediments form a distinctive pattern, with ore-bearing sulfides in the center of a belt, then carbonates on either side, and finally oxides on either edge. Ridler believes that the sedimentary pattern arises from variations in acidity, oxidation potential, and temperature in the area surrounding the vent of a submarine hydrothermal circulation. The less soluble species (which include the metal sulfides) precipitate nearest the vent, carbonates next, and finally oxides. Ridler has been able to trace exhalite patterns for hundreds of kilometers along mineral belts in Canada. These markers of past hydrothermal systems are now being used in exploration.

What is still unexplained, as far as the role of seawater in leaching metals from submarine volcanic rocks is concerned, is exactly what controls which metals are leached, and a number of theoretical and experimental investigations of the geochemistry of hydrothermal systems are under way. Nonetheless this process has been proposed as responsible for the Troodos-type ores found on Cyprus, which are associated with spreading centers; the young, massive sulfide ores associated with island arcs above subduction zones; and many older massive sulfide and precious metal deposits.

The interaction of seawater and crustal materials, and its implications for ore formation, may go beyond the presence of hydrothermal systems. Fyfe believes that chemical reactions involving seawater are not restricted to the area around spreading centers but continue as the oceanic plate moves. In particular, he believes that rocks in the upper portion of oceanic crust continue to change composition and to become more hydrated, locking in large volumes of water and other volatiles. Since most newly formed oceanic crust is eventually subducted and returned to the mantle, the plate tectonic process removes water from the oceans at a rate that, according to Fyfe, would deplete the oceans every 300 to 500 million years if it did not return. Thus Fyfe envisions a massive exchange of water and other volatiles between the crust and the hydrosphere which may be important in the production of volcanic and igneous rocks and their ore deposits above subduction zones. For example, melting of the oceanic crust being subducted is thought to be facilitated by the presence of seawater in the upper portion of the slab.

The ongoing reevaluation of ore formation processes in the context of plate tectonics is so broad that in some cases it is difficult to distinguish between it and more fundamental investigations of the earth's evolution. Some researchers, for example, are looking into the idea that the earth's oceans did not gradually evolve by degassing of the mantle but instead formed early in the planet's history and have been gradually diminished since then—a possibility suggested to them by mineral evidence. Thus whether or not the new metallogenic ideas improve our ability to find and extract metals, and they probably will, they promise to enliven geology for years to come.—ALLEN L. HAMMOND