Minerals and Plate Tectonics: A Conceptual Revolution

Drastically higher prices for oil and declining U.S. production have drawn attention to supplies of other key industrial materials, especially minerals. Although immediate shortages do not appear likely, some authorities have expressed concern about the extent of U.S. dependence on other countries for supplies of chromium, manganese, and other metals. Moreover, depletion of high grade ores and environmental regulations affecting mining and ore processing are expected to increasingly constrain the availability of minerals.

Fortunately, renewed interest in minerals comes at a time of excitement and sweeping new ideas in the study of mineral deposits. The new ideas reflect the impact on economic geology of plate tectonic models for the evolution of the earth's crust. Many ore deposits, for example, are now known to occur at present or past boundaries of the huge crustal plates whose movements have shaped and reshaped the earth's surface. What ores are formed and where they are placed in the crust, it is proposed, depend principally on the tectonic history of a particular region; several models of the processes involved have been put forward. Similarly, it is proposed that the interaction of seawater with cooling volcanic rock is the principal means by which many metals are extracted and concentrated into economically valuable ore bodies; thus hydrothermal rather than magmatic processes are the key to understanding the geochemistry of ore deposits. These proposals and others have stimulated a host of more detailed investigations. Many geologists believe that these developments portend a fundamentally new understanding of the origin of minerals and are laying the scientific foundation for a new era in mineral exploration.

Not all mineral deposits fit the new conceptual framework, but many major classes of metal ores are explicable in its terms. The evolving theoretical models provide detailed if still controversial explanations for the chemistry, mineralogy, and stratigraphic location of these deposits and thus a host of clues with which to look for still undiscovered mineral deposits, some of which are finding tentative use in the mineral industry. They also have implications for the evolution of the earth's crust; similarities between recent and more ancient ore bodies are seen by some researchers as evidence that tectonic processes not unlike those of the present geologic era occurred throughout most of geologic history.

Many metallic ores are now widely recognized to be of volcanic origin in the sense that they occur in volcanic or igneous rocks and were formed at the same time as those rocks. According to plate tectonic theory, volcanism occurs in several circumstances: at diverging plate boundaries (mid-ocean ridges or other centers of seafloor spreading), where mantle material rises to form new oceanic crust; at converging boundaries, where crustal plates descend into the mantle in a process known as subduction, leading to volcanism that forms chains of mountains or oceanic island arcs; and, less frequently, over hot spots caused by ascending plumes of mantle material (Fig. 1). Each of these processes, except possibly the last, is now thought to give rise to a characteristic type or types of ore deposits.

One of the clearest examples—and one which has had major impact on the thinking of economic geologists—is found on the Mediterranean island of Cyprus, long a rich source of copper. The copper sulfide ore occurs in the Troodos area of Cyprus in a distinctive sequence of rocks: on top, sediments of a type formed on the ocean floor; beneath the sediments, pillow lavas formed when molten volcanic material erupts into seawater; farther down, vertical sheets or dikes of basaltic rocks formed as rifts or cracks in the ocean floor are filled from below with volcanic material; and on the bottom, ultramafic rocks (rich in magnesium and iron) that are believed to be characteristic of the earth's mantle. This progression of rock types is known to geologists as an ophiolitic sequence. About the time that economic geologists recognized copper sulfide deposits as an integral part of these rocks on Cyprus, other geologists recognized the ophiolitic sequence as exactly that which should be formed at a mid-ocean ridge. Thus the Troodos area is now thought to be a largely unaltered piece of oceanic crust thrust up when Cyprus was formed, and the mineral deposits it contains are thought to be characteristic of those formed at mid-ocean ridges.

The minerals include sulfides of copper, iron, and sometimes zinc embedded in the pillow lavas, small masses or "pods" of chromium ore near the top of the ultramafic layer, and asbestos deposits, also in the ultramafic rock. Although not present on Cyprus, lateritic nickel deposits are sometimes found in sections of oceanic crust where ultramafic rock (which is rich in nickel) has been exposed and weathered. Mineral deposits of the Troodos type are found in many parts of the world, including the northeastern United States and eastern Canada. They range in age from the geologically young deposits of Cyprus to older deposits that originated as many as 600 million years ago.

A second major type of mineral deposits—large bodies of low grade ores known as porphyry coppers—are commonly associated with converging plate boundaries. A prime example is the extensive copper deposits in the Andes, where the eastward-moving oceanic crust of the Pacific plunges under the lighter material of the westward-moving South American continent. Partial melting of the downward-moving oceanic plate is believed to generate magmas that rise through the overlying continental rocks, sometimes reaching the surface to form volcanoes. The upper portions of the pipelike stalks or cores of these magmatic intrusions into the surrounding continental rock often contain copper and molybdenum, and sometimes gold and silver as well. Several investigators have studied this process, including Richard Sillitoe, formerly of the Instituto de Investigaciónes Geológicas, Santiago, Chile, and now at Imperial College, London; P. W. Guild of the U.S. Geological Survey, Reston, Virginia; Andrew Mitchell of Oxford University; and M. S. Garson of the Insti-

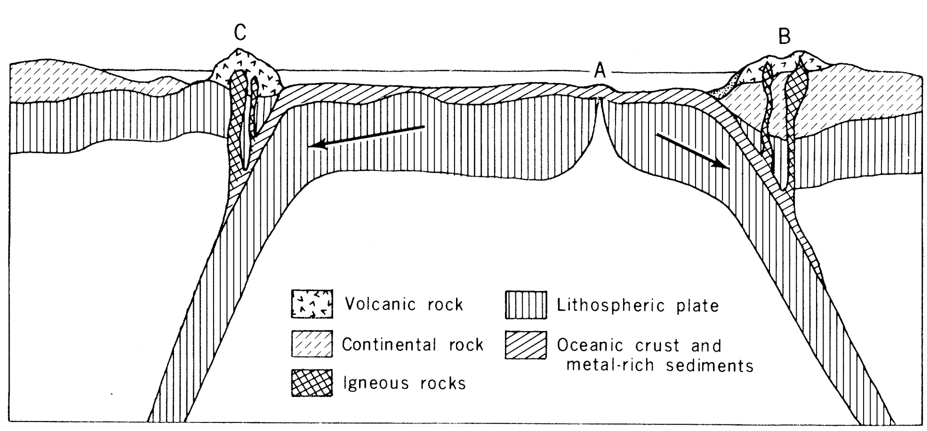

Fig. 1. Schematic showing three different ore-forming environments and the plate-tectonic phenomena postulated to give rise to them: (A) a mid-ocean ridge or rise; (B) a subduction zone underlying a continental margin; and (C) a subduction zone underlying an island arc. Arrows indicate direction of motion of the plates.

tute of Geological Sciences, London. They propose that formation of porphyry ore deposits is a normal facet of the processes that generate the igneous rocks in which they occur. Sillitoe, for example, suggests that the metals of the porphyry ores were initially incorporated in oceanic crust at the mid-ocean ridge, transported horizontally by the movement of the plate, and then released as the downward-moving plate is heated.

Porphyry copper deposits account for more than half the world's supply of that metal. In addition to the porphyry deposits in the Andes, there are deposits in western North America, in parts of the Alpine belt of Europe, and in Iran and Pakistan. Although normally associated with continental rocks, porphyry deposits are also found in some of the larger volcanic islands of the southwest Pacific. Most of these deposits are geologically youthful, less than 200 million years in age. Highly eroded remains of older deposits have been found, however, in northeast North America. Even in the richest porphyry ores, however, copper rarely exceeds 1 percent, and 0.5 percent is more common, so mining consequently involves extracting and processing large tonnages of ore. The association of porphyry deposits with the subduction of oceanic crust into the mantle and the concomitant magmatic activity is so strong that it has been the basis for exploration efforts. A major exception, however, may be the porphyry deposits in Arizona, which according to J. David Lowell of the University of Arizona do not show evidence of a subduction zone. In recent years new porphyry deposits have been found in Okinawa, Panama, and British Columbia.

Deposits of a third distinctive type, known as massive sulfides because they often occur as large, nearly pure lenses of high grade ore, are found in modern island arcs and some geologically older island arc materials that are now incorporated in continental margins. These deposits, like the porphyry coppers, are associated with the convergence of two crustal plates. They are typically polymetallic, containing copper, zinc, lead, gold, and silver.

The prototype deposits for investigators unraveling the origin of these massive sulfides have been those in northeast Japan. This black "Kuroko" ore is thought to have been formed by submarine volcanic processes and deposited in shallow, nearshore environments late in the evolutionary history of a volcanic island chain. The volcanic rocks associated with these deposits are correspondingly highly evolved and often include fragments from explosive eruptions. Marine sediments are also often found with such deposits.

A second variety of massive sulfide ores—those of the Besshi type—are also found in island arcs. Besshi copper and iron sulfide ores (named after a deposit on Shikoku Island, Japan) are, like the Kuroko ores, commonly thought to be submarine volcanic emissions, but deposited on the underwater slopes of volcanoes early in their evolution. Still other classes or subclasses of island arc mineral deposits, corresponding to additional stages in the evolution of these fragments of land, can be distinguished. In fact, a model of the process proposed by Mitchell and J. D. Bell, also of Oxford University, describes seven such stages. They give the timing and accompanying rock types for the forma-

Plate Tectonics: How Far Back?

The impact of plate tectonics on mineral geology is rapidly becoming a two-way relationship. Direct evidence from the sea floor for plate motions and related tectonic mechanisms exists only for the last 200 million years of the geologic record, but metallogenic and other geologic data support the idea that these phenomena extend back at least 600 million years. Thus mineral deposits indicative of crustal formation at mid-ocean ridges and of subduction of crustal material into the mantle to form volcanic island arcs and continental mountain belts are found throughout that period. The key question is what happened before 600 million years ago, in the Precambrian era that includes 80 percent of the earth's history.

Among the oldest rocks of Precambrian continental areas are the mineral-rich greenstone belts, which contain volcanic rocks resembling those of modern island arcs in both chemical composition and physical properties. Greenstone belts are found in Canada, Australia, South Africa, and other areas of very old crust. According to A. M. Goodwin of the University of Toronto, the proportions of basalt, andesite, and rhyolite in these ancient volcanic belts are similar to those in recent island arcs—about 60 percent basalt, 30 percent andesite, and 10 percent rhyolite. In both geologic settings the volcanic piles show a common stratigraphy—basaltic rocks on the bottom, andesite above them, and rhyolite on top. The Precambrian rocks also show evidence, he finds, of explosive volcanism, a characteristic of island arc volcanoes.

Mineral deposits in greenstone belts and in island arcs are quite similar too, especially those known as massive sulfide deposits (including copper, lead, and zinc ores) and the precious metal deposits that occur with them. These ores are widely believed to be of submarine volcanic origin in both Precambrian deposits and island arcs. The massive sulfide deposits are typically found embedded in rhyolitic rocks near the top of the volcanic pile, while gold, some observers believe, is commonly found lower in the volcanic sequence.

In view of these similarities, some researchers have proposed that Precambrian greenstone belts represent ancient island arcs. If correct, this view would imply that plate tectonic activity existed well back into the earth's early geologic history and that the formation of island arcs and their accretion to continents has continued for perhaps 3 billion years.

There are some substantial dissenting views, however. R. H. Ridler of the Geological Survey of Canada finds no evidence for large-scale horizontal movements of crust in the early Precambrian. He also points out that island arcs are typically asymmetric, reflecting their tectonic origin (with an oceanic trench on one side and a shallow basin on the other); greenstone belts, on the other hand, show a symmetry that he believes is more characteristic of development in a basin. R. W. Hutchinson of Western Ontario University distinguishes three types of massive sulfide mineral ores—two modern types and one characteristic of the ancient ores. In his view the ores are similar, but differ in ways that suggest an evolution of ore types. This reflects a corresponding evolution in tectonic mechanisms, away from some predecessor mechanism to plate tectonics, which formed the modern island arcs. In contrast, Andrew Mitchell and J. D. Bell of Oxford University believe the evidence suggests that "ore-forming processes in [island] arcs have changed little during the last 2×10^9 years."

The debate is still wide open. But it is apparent that evidence from ancient mineral ores and the rocks in which they occur will play a central role. It is a debate that investigators interested in the evolution of the earth's crust will watch with interest.—A.L.H.

tion of Besshi and Kuroko massive sulfides, porphyry coppers, and exogenous mineral deposits (those not formed at the same time as the surrounding volcanic rocks) found in island arcs.

As the plates move, island arcs may be swept into and incorporated in continental masses. And because continents collide, it is not surprising that island arc fragments have been identified in what are now continental interiors. This is significant because a second and major source of massive sulfide and precious metal deposits is the so-called greenstone belts found in ancient Precambrian areas of continents. These belts have historically been the source of much of the world's mineral wealth, with rich deposits ranging from iron ores, important gold deposits, copper and zinc to lead and silver ores.

The Precambrian mineral ores, like younger massive sulfide deposits, are believed to result from submarine volcanic processes. The volcanic rocks associated with these ancient mineral deposits also show chemical and mineralogical similarities to those of island arcs. Hence some geologists believe that greenstone belts represent ancient island arcs. Since some of the Canadian belts date back at least 3 billion years, this would imply the existence of tectonic mechanisms similar to those that create modern island arcs throughout much of the earth's history, a conclusion that is still controversial (see box). If crustal plates did exist in the Precambrian era, 600 million years ago and earlier, they were apparently much smaller but possibly more numerous; the greenstone belts tend to be hundreds of kilometers in length, not thousands of kilometers like modern island arcs. In any case, the similarities and differences between old and young ore types may be important for exploration—rocks, presumably ancient, that underlie the upper portions of the continents are largely unexplored.

A final class of mineral deposits, whose tectonic derivation is much more speculative, are those ores thought to be formed within a crustal plate, rather than at its boundary. Here the proposed mechanism is penetration of mantle material up through the crust to form a hot spot, possibly as a result of the mantle plumes which have been hypothesized as a driving force for the motion of the crustal plates. Hot spots, investigators are suggesting, may have heated the crustal rock, mobilizing metals from sedimentary or crustal materials and concentrating and depositing them nearer the surface. Guild, for example, proposes that the rich lead-zinc ores of the Mississippi Valley may have originated in this fashion. Similar proposals have been made for lead-zinc deposits in northwest Africa. In some instances, Guild believes, the minerals themselves have come from the mantle, propelled up through the crust by the heat of the plume. Diamonds, niobium, and some rare-earth deposits, for example, are associated with the explosive eruption of mantle materials to the surface and may be attributable to a plume mechanism. Heat from the mantle, perhaps rising near subduction zones, may also provide the energy to mobilize metals present in lower crustal rocks and concentrate them into ore deposits in some circumstances. This mechanism has been proposed to explain the eastward shift from dominantly copper to dominantly lead-silver ores in western North America, and the repeated emplacement of tin ores in only a few areas of the earth.

Newfoundland Mineral Deposits

A striking illustration of the new models of mineral formation is their application to Newfoundland by David F. Strong and his colleagues of the Memorial University, St. John's. Before the opening of the Atlantic Ocean and the separation of North America from Eurasia about 200 million years ago, according to plate tectonic theory, the Appalachian mountains of eastern North America and the Caledonian range in Britain and Norway formed a continuous mountain belt. Although the details of how this ancient mountain range was formed are still a matter of debate, the basic process is thought to have been the opening and eventually the closing of a predecessor or "proto Atlantic" Ocean between about 600 and 450 million years ago. Since Newfoundland sits astride the Appalachian-Caledonian range, it is in many ways an ideal laboratory for exploring how a tectonic cycle that involved the formation and then destruction of large amounts of oceanic crust affected the formation of metallic ores.

The Newfoundland investigators find that most mineral deposits on the island can be classified in terms of specific plate tectonic origins. They include Troodos-type ores in ophiolitic rock assemblages, Kuroko-type ores in volcanic rocks typical of island arcs, porphyry copper deposits in igneous rocks, and Mississippi Valley–type lead-zinc ores.

The geology of Newfoundland is complex and the ore deposits are distributed in both age and location. The eastern and western parts of the island are composed primarily of ancient Precambrian rock (older than 600 million years), while the center part of the island is of more recent origin, formed during the proto-Atlantic event and sandwiched in between the older crust as the ocean basin disappeared. Along the western margins of the island are limestones and dolomites, some of which contain Mississippi Valley–type lead-zinc ores. These rocks were apparently deposited in shallow waters during the early part of the proto-Atlantic era. Also on the western shores are ophiolites with Troodos-type ores, representing blocks of oceanic crust thrust up onto the limestones and Precambrian rocks. Belts of ore-bearing ophiolites are also found in the central section of Newfoundland, as are volcanic rocks that contain Kuroko-type polymetallic ores. In the eastern part of the island are porphyry ores, apparently emplaced somewhat later in Newfoundland's history as oceanic crust was subducted beneath continental crust in the final closing of the ancient ocean. The pattern, as the investigators see it, is lead-zinc deposits in the west, then copper and iron ores, then overlapping bands of copper, lead, zinc, gold, and silver deposits, and finally occurrences of copper, molybdenum, and tin deposits in the east.

According to Strong, this pattern of mineral deposits with identifiable plate tectonic origins may well be common to the entire Appalachian-Caledonian chain. Limestones bearing lead and zinc are found from Norway to Alabama, always on the westernmost edge of the mountain chains. Also extending along the length of the chain are ophiolites with, in many places, Troodos-type copper and iron sulfides. Known occurrences of polymetallic island arc deposits are more scattered, according to Strong, but appear to lie in the central and eastern portions of the Appalachians. Tin occurs in Alabama and Virginia still farther east. The mineral patterns constrain tectonic models for the Appalachians, especially by implying the existence of a southeastward-dipping subduction zone during the formation of the mountain belt, according to Strong. They also have implications for mineral exploration, he believes, since discoveries in Norway could lead to similar finds in Newfoundland and Tennessee or vice versa. Exploration of Newfoundland and eastern Canada has, in fact, accelerated in the past several years.

The new models of ore formation are far from complete and are still some distance from being completely accepted. Still newer ideas concerning the geochemical processes involved and the role of seawater are being proposed, and these will be the subject of a second article. But perhaps the most significant aspect of the emerging synthesis between plate tectonic theory and metallogeny is the prospect that, in a resource-hungry world, mineral exploration can increasingly be guided by a detailed understanding of how, and perhaps where, ores are formed and deposited.

—ALLEN L. HAMMOND