OROGENESIS AND ORE DEPOSITS

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Abstract

Ore-forming processes are discussed in relation to the hypothesis that the earth originally had a basaltic crust, and that the continents have been derived from this crust and the mantle. The transformation was accomplished by a combination of disintegration, decomposition and redistribution of rock materials at the earth's surface and reorganization of geosynclinal accumulations during orogenesis.

Limited concentrations of metals may have formed during the solidification of the outer part of the earth, but these could not become available as ores except through drastic later disturbances of the outer crust.

Ore-forming processes are considered in four groups: (A) Concentration by Surface Processes; (B) Concentration during the Filling of Geosynclines; (C) Concentration during Orogenesis; (D) Concentration during Stable Platform Modifications.

Surface processes produce several types of ore deposits and help to shape the "charges" of geosynclines.

During the accumulation stage in geosynclines, deposits enriched in metals may form (1) from the differentiation of basic intrusives as magmatic sulphide or oxide deposits, or as cavity filling, replacement or hotspring deposits formed by late stage hydrothermal extracts from these magmas (2) through the outward migration of quantities of water originally included in the sedimentary fill. This water, with many substances dissolved, including metals, ranges in temperature from cool to hot, depending on the depths reached. In the late stages of accumulation, water in the deepest parts should be above the critical temperature and metamorphic changes in the sediments may have set in on an appreciable scale. All deposits formed before major deformation sets in, must be raised high above their level of formation to become available as ores. This is accomplished during the deformation stage and such ore deposits are normally deformed with the rest of the rocks.

During the deformation stage in geosynclines, water solutions are moved about; metamorphic changes result in driving off of more water, both free and combined, and these solutions may form additional ores. Differential melting and solution of sedimentary and volcanic materials in deep parts gives rise to magmas with more or less metals, depending on the make-up of the material melted. Injection of magmas to higher levels results in driving off more water from the surrounding rocks and the magma itself may, at a late stage in its crystallization, yield solutions capable of forming metal-rich cavity filling and replacement deposits. Such injections and ore forming processes continue during a prolonged period following the climax of deformation. Those deposits brought close to the surface by subsequent erosion are available as ores, if rich enough in metals.

Stable platform adjustments may result in the formation of ores related to layered basic intrusives, or to volcanic centres; also ores of Zn, Pb, Cu, V and U in cover rocks.

To improve understanding in discussions of deposits formed by hot water solutions, it is desirable that the word hydrothermal, used in reference to ore deposits or solutions, be stripped of all implications that the deposits or the solutions were derived from magmas.

Introduction

As a friend and admirer of Dr. J. E. Hawley through many years, I consider it a privilege and an honour to be included amongst the contributors to this volume. Dr. Hawley's contributions have been numerous and broad in range, but much of his work has been directed toward greater understanding of the nature and genesis of ore deposits. The topic chosen for discussion is in this field, and while it is less specific in character and more theoretical than is customary for contributions to this journal, it is my hope that it will be of some interest to Dr. Hawley and readers generally.

It is well recognized nowadays that in the Western World at least, the day of finding ore deposits by systematic search for and examination of rock outcrops is rapidly drawing to a close. Use of geometrical projections and geophysical tests will help to extend known ore-bearing zones and fields into covered areas, but the discovery of new fields with no surface expression must depend on broad-scale geological studies, including geophysical data, systematic deep probing, and complete mineralogical and chemical study of the samples so provided. Success in such work will depend not only on a comprehensive knowledge of ore deposits and their settings, but on the completeness and accuracy of our knowledge of earth processes generally, and how and where the ore forming processes fit into the general picture.

Ore forming processes operating at or near land surfaces have been studied directly, and differences of opinion have to do with details. Those operating within the earth's body are known only by reasoning from the results produced in accessible parts of the earth. The information available is scant, and explanations offered are correspondingly numerous. It is desirable that the possible early distributions of metals and the processes available for their extraction and concentration be considered in relation to each of the hypotheses advanced. However, in this paper I will give merely a personal evaluation of possibilities consequent on what appears to me to be the most probable history of the outer part of the earth.

Evolution of the Earth

Most geologists and geophysicists now agree that the outer part of the earth at least was molten at an early stage in its history. At this stage, strong tides and convection should have prevented any more than a crude gravity stratification in the outer part. Crusts would have formed at the top only to sink, because of their higher density, and disappear by dissolving. The first continuous chilled layers formed must have been short-lived, because the repeated complex stressing by tides and convection currents would have caused rupture, sinking and resorption in the liquid. Solidification probably occurred ultimately, mainly from the bottom up. At some late stage, chilling at the surface may have produced a crust thick enough to sustain the great stresses to which it would have been subjected or at least to maintain continuity, with the aid of rapid sealing of fractures by chilling of the liquid rising from beneath. However, for this to occur, the liquid must have been near the freezing point, so a continuous solid crust with a complete liquid layer beneath could have existed for only a short time. Thereafter, only pockets of liquid remained in the outer part of the earth which was otherwise solid. Eventually a situation was reached where loss of heat by conduction and radiation was approximately balanced by the internal output from radioactive minerals and other sources, and stability in the solid state was approached. Thenceforth general stability was upset locally from time to time by residual irregularity in the internal heat output, the shifting of surface materials under erosion, and the daily and secular changes in stressing by external forces. Adjustments to restore the balance were effected mainly by elastic strain and rupture in the outer part of the crust, and by more complex processes involving recrystallization and partial melting at greater depths, where higher temperatures prevail. This is the situation at present.

Geophysicists now appear to be in agreement that the outer part of the earth is composed of a crust embracing the continents and the floor of the ocean, resting on a "mantle" of markedly different material, similar in its physical behaviour everywhere. Crust and mantle are separated by the Mohorovicic discontinuity at an average depth of 10 to 11 km. below sea-level under the oceans, and 30 to 40 km. deep under the continents. This discontinuity is marked by a rapid increase in the velocity of compressional and distortional waves from 6.7 km./sec. to 8.1 km./sec. in the case of the longitudinal waves, and from 3.8 to 4.7 for transverse waves (Gutenberg, 1955, p. 25 and 28). Comparison of these figures with velocities determined experimentally for rocks suggest a composition close to peridotite or eclogite for the upper mantle, and basalt for the oceanic crust and the lower parts of the continents. The upper part of the crust has an average composition near that of granodiorite.

In an earlier paper, I have supported the view that the original crust of the earth was formed mainly of basalt, and that all the continents have been built up through a succession of deformations in orogenic belts

(Gill, 1961). The existing mountain systems with moderate to high relief, where the largest number and the greatest variety of known ore deposits occur, are only the younger members of a long succession extending back to the beginning of the Precambrian. Each mountain system in succession has been worn down to a low general level by erosion processes, the debris being in part laid over the roots of older systems, forming a superficial blanket of sediments in interior parts of continents. In part it was carried into the marginal parts of the sea contributing to the fill of new geosynclines, and in part into the deeper ocean basins.

The continents, according to this hypothesis, have been built mainly from basalt derived from the original crust, and from the mantle by differential melting; also, in part, from peridotite injected from the mantle. The extraordinary variety of rocks now found in the continents and their distribution are explained by the working over of basalt and peridotite in the erosion cycle and the reorganization of some of the products, deposited in geosynclines along with extrusions and intrusions from the mantle, by orogenic processes. Erosion products of old mountains go into the formation of new, so some parts of the crust have been worked and reworked in this complex milling-smelting process.

The Formation of Ore Deposits

If the views outlined above are accepted, it follows that all the ore deposits must have been derived by more or less complex processes of extraction from basalt and peridotite. In the early stages strong stirring by tidal and convection currents would have prevented the formation of any near-surface concentrations of metals. Only when the liquid layer had been reduced to a few tens of kilometers could such concentrations have developed within a range to be reached and moved towards the surface by orogenic processes in later times. Whether layers of sulphides or concentrations of metal of other types formed at this stage is debatable, but it appears almost certain that some would have formed at a later stage of the solidification process when the liquid layer had been reduced to isolated pockets of basic magma. By analogy with the layered basic intrusives found at the surface now, these would consist of accumulations of nickel-copper sulphides toward the base, chromite-rich and platinum-rich layers at higher levels, titaniferous magnetite still higher, associated with norite, and copper-zinc and zinc-lead deposits associated with the more acidic facies towards the top and outward in adjacent rocks. These deposits could only become available as sources of metals by becoming involved at a later time in deep-level changes, most probably those related to mountain building. They might, for example, be moved as a sulphide magma or be incorporated in a silicate magma and moved towards the surface in a more complex manner, ending up either dissipated through large masses of rock, or as a deposit or deposits of completely different form and composition. Transfer as metal vapours or volatilized metal compounds as recently advocated by Brown (1950), undoubtedly occurs at high temperatures, but evidence from experiments has so far given no support to the idea that this process is a major one in the formation of ores of the common metals (McDougall *et al.*, 1961). It should be noted, however, that much remains to be learned about the behaviour of metals and metallic compounds in contact with gaseous solutions at high temperatures and pressures.

When the temperature at the surface dropped below the boiling point of water, oceans accumulated and stream erosion of land surfaces commenced. As the water depths increased, the oceans would, in time, have produced a shallow cover over the whole surface, except for isolated protuberances due to irregularities produced by earlier volcanic eruptions. Debris from weathering and erosion was swept into adjacent troughs and basins initiating the first geosynclines. Because the temperature gradients near the surface were relatively steep in these early stages, the crust capable of withstanding stresses of any magnitude was relatively thin, and failure under compression of whatever origin must have occurred more frequently with narrower, sharper downwarpings under load, hence more frequent deformation and less lofty mountains.

Observations of sediments in the Precambrian shields indicate that break-down of rocks under weathering was less complete than in later times. Deformation and igneous activity within orogenic belts developed along the same general lines in the Precambrian as in subsequent geologic time.

Differences between the older and younger sediments were most probably caused by secular changes in the atmosphere and the ocean. These, and the thickening of the strong crust, should have caused some differences in igneous rock compositions, but too little information is available as yet to enable one to define these differences with any certainty.

To form an ore deposit, metals from a concentration at depth, such as those that may have formed during the late stages of solidification of the earth, must have been moved to a location near the earth's surface, or else metals disseminated through solid basalt or peridotite must have been concentrated at a later time by one or more of numerous processes known to be operative. These concentration processes will be considered in four categories:

(A) Concentration by Surface Processes.
(B) Concentration during the Filling of Geosynclines.
(C) Concentration during Orogenesis.
(D) Concentration during Stable Platform Modifications.

(A) *Concentration by Surface Processes*

Rocks at the surface of the earth are broken down and metals may be concentrated (*a*) residually, (*b*) mechanically, as placers, (*c*) by transport in solution and deposition at shallow depths as supergene enrichment deposits, or (*d*) by transport in solution and deposition in more than average proportions in basins along with other sedimentary materials. The formation of ores in these ways has received much attention and is fairly well understood.

We have only recently become aware of concentrations of possible economic importance as nodules containing copper, manganese and other metals on the floors of the deeper parts of the oceans. Too little is known about these at present to permit one to gauge their importance. The mining problems presented are imposing.

Finally, it should be observed that surface processes prepare and contribute a substantial part of the filling of geosynclines. Metals are more concentrated in some parts than in others and the mineral forms and associations differ from place to place. The variations in the composition of the geosynclinal fill must exert an important influence on ore formation during orogenesis.

(B) *Concentration during the Filling of Geosynclines*

Geosynclines start with depressions that are natural receptacles for sediments. Commonly they develop along continental margins, though a few may have formed along rift zones. The presence of basic volcanics as early fill in many, indicates that adjustments and local fusion in the crust or sub-crust along these belts, started early, possibly as soon as the trough formed, or even before.

Mixes within the troughs are variable. In all cases sea water is an important constituent. Some of the sediments may be enriched in metals, others depleted. The mix is initially out of equilibrium, and it tends to become more so as loading continues and the mass moves into deeper and hotter parts of the earth. The sediments pass through a series of changes. First, there is compaction, loss of water and minor reorganization chemically. This continues as the sinking and loading progresses. Some metals may be moved in the cool solutions squeezed out, but there is little to indicate that these solutions have been very effective in ore formation. Basic intrusives and extrusives may, however, raise the temperatures and drive off pore water with metals dissolved. These solutions may be channeled along zones of adjustment, and some may even reach the surface to produce spring deposits.

At 10,000 to 15,000 feet (3 to 4.5 km.) depth temperatures are above 100° C. As sea water at such temperatures is progressively squeezed out from pores and moves towards the surface, it becomes increasingly probable that metals and other substances will move with it.

Here it may be noted that, despite recent criticisms (Brown, 1947; Sullivan, 1954) the evidence for transportation of metals in hot water solutions to form ore deposits is strong, even though the details of the processes are not, as yet, well understood (Smith, 1940; Soles, 1959; Cloke, 1961; Roedder, 1962; Barnes, 1962).

At depths of 36,000 to 45,000 feet (11 to 12.5 km.) water boils under the hydrostatic head and cannot exist as liquid much below 12.6 km. depth because the temperature is above the critical point.

At depths greater than 6 miles (10 km.) metamorphic changes become important. The figures given are based on a normal temperature gradient. Depression of the isogeotherms probably occurs for a time due to sinking of cool surface accumulations into hotter zones, or they may rise markedly if large amounts of volcanics are involved.

Any mechanical shifts in the mass of sediments and volcanics during the early stages of accumulation and compaction will cause movement of solutions toward dilatant zones. Since volcanics and some sediments may fracture and retain openings to greater depths than those so far considered, we can picture a connected complex of metal-bearing solutions passing through a considerable vertical range and varied chemical environments. Precipitation of metals by drop in temperature by reaction with wall rock, or with other solutions, or by loss of gases in lower pressure zones could form concentrations that have nothing to do with magmas. Such concentrations could not, however, become available as ores until a major deformation in the belt had raised them to higher levels, and had produced a thickened mass of light material, so that erosion could cut deeply when isostatic adjustment was approximately attained. This means that they would normally be deformed with the rest of the rock masses. Since this could be accomplished at temperatures well above those of their initial formation, they would almost certainly recrystallize, and may also be radically changed in shape and position in relation to associated rock masses, in the process.

(C) *Concentration during Orogenesis*

It is interesting to note that severe deformation sets in in most geosynclines when accumulations reach thicknesses of 30,000 to 40,000 feet

(12 km.) where, on the normal temperature gradient, the critical temperature of water is passed, and metamorphic changes begin to gain prominence in most rock masses. These changes would certainly be accompanied by mechanical adjustments developing heat. Heat is also emitted when fine-grained sediments recrystallize to coarser grained structure (Cumberlidge, 1959) and possibly also as a result of certain metamorphic reactions (Saull, 1955). Because of these effects, temperatures continue to rise in the deeper zones. Much of the supercritical water no doubt moves outward towards the surface, carrying metals and other substances; some is bound in the hydrous minerals of low and medium grade metamorphic facies. At higher temperatures most of the bound water goes too, and high grade metamorphic rocks are formed.

Movement of metal ions outward from hot centres can occur independently of water solutions, and this process almost certainly contributes to ore formation (MacDougall, *et al.* 1961). Whether it has by itself ever produced an ore body is, however, open to question.

If temperatures rise high enough, differential melting sets in. In the presence of water, quartz and feldspar melt first. Such extracts may yield pegmatites. Further rise in temperature may give a granitic magma, or, with admixture of basic materials, some of the intermediate compositions.

In situations where water and other volatiles cannot escape readily, melts may be heavily charged with water and would probably be most effective in producing hydrothermal ores of magmatic derivation. If some of the sediments incorporated in the melt were enriched in metals, the situation would be especially favourable.

The number and sequence of stages of accumulation and deformation in major orogenic belts are variable. The sum total of the effects is a marked shortening, whatever the causes, for a thickness of upward of 50 km. is produced from materials initially measuring no more than 17 km. This would require shortening to about $\frac{1}{3}$ of the original width. Vertical movements as advocated by Carey (1958) and Bellousov (1960) cannot by themselves produce the observed results.

In deeper sections, plastic materials are squeezed and distorted. Fluids are squeezed upward into the meso- and epi-zones where elastic strain and rupture become more prominent, and structural control of minor intrusives and ore-forming fluids is evident. Fluids reaching positions of lower temperature cool and may crystallize under relatively quiet conditions where, however, periodic stressing may cause injection of a series of magmas with compositions forming a commonly observed sequence increasing in acidity from oldest to youngest. Associated ore deposits would depend on the source of the magma. If it were a relatively unpolluted gabbroic magma from initial crust or mantle, the usual layered intrusive assemblage should result. If it were an extract from sediments, it would normally be initially enriched in silica and alkalis, but with increase in temperature many other things may be incorporated and what ores, if any, ultimately come out, would depend to an important degree on what went into the melt in the first place. Other important factors would be the level to which it was injected, and the stressing or otherwise during cooling and crystallization. A vast array of vein and replacement deposits, with many of the rarer as well as the common metals appear to have formed from late stage emissions, mainly water solutions, derived from such magmas.

The rise of magmas into cooler zones, or the squeezing of plastic high-temperature bodies partly or largely solid into cooler parts of the crust, would result in further driving off of water and volatiles from surrounding rocks. These may be channelled into fracture or shear zones, as recently advocated by Boyle (1959) from studies of the Yellowknife district. Such deposits are akin to deposits discussed in relation to the pre-deformation or early deformation stages. They may or may not be deformed at a later stage.

In the Soviet Union the strong, persistent effort to catch up to the Western World in industrial production has involved the training of large numbers of scientists and technicians, and the launching of a massive attack on the vast expanse of Northern Asia. This work has been done in a comparatively short time, following a uniform system, and in the light of knowledge and concepts arrived at piecemeal and laboriously over earlier years by workers in the Western World. It is interesting to note that they have adopted and elaborated details of the orogenic cycle, and, more recently, have attempted to systematize and correlate with it their findings from the studies of ore deposits.

A major effort along these lines has been made by a group working in the All-Union Scientific Research Institute of Geology of the Ministry of Geology and Conservation of Natural Resources (VSEGEI). This group is headed by Yu. A. Bilibin who summarized their findings (Bilibin, 1955).

McCartney & Potter (1962), have summarized some of the VSEGEI findings and have tested them in relation to what is known about the Appalachians in Canada with fairly satisfactory agreement.

Briefly, Bilibin and associates conclude that a typical mountain system results from three distinct stages of accumulation, deformation and intrusion, followed by a prolonged dying out period.

Stage 1 The geosynclinal fill is characterized by abundant volcanics, most commonly spilite-keratophyre with some andesite, basalt, and albitophyre. Associated sediments are mostly jaspers, siliceous shales, reef limestones, and carbonate masses of volcanic origin. Conglomerates, sandstones and shales are minor or absent. The stage ends with folding and intrusion of ultrabasic and basic magmas. Ore deposits are predominantly magmatic–platinum group, Cr, Fe, Ti, V, Ni, Co, Cu, P.

Stage 2 Terrigenous sediments are more important, volcanics less so, carbonate rocks variable. The stage ends with folding and intrusion of small bodies ranging from gabbro to plagiogranite or grano-syenite, regarded as differentiates of the earlier basic magmas. Increasing rigidity results in consecutive stages of disruption. Ore deposits are replacement and vein deposits of diverse character—Zn, Pb, Ag, Au, Fe, Cu, Ba, Ni, Co, As.

Stage 3 Terrigenous sediments predominate, carbonates and volcanics are sporadic. Volcanics are intermediate to acidic in composition. The cycle ends with folding and granitic intrusions of great bulk. The granites are not related to basic magmas. Ore deposits are predominantly hydrothermal vein and replacement deposits, some pegmatitic—Sn, W, Mo, Au, Li, Be, B, Ta, Nb, etc.

The waning stage is a protracted period of uplifts, faulting, limited deposition of continental and estuarine sediments with coal, salt, gypsum and petroliferous rocks, followed by some injection and extension of granitoid differentiates of a basic magma, and finally undifferentiated basic magma.

The summation does not conflict with the hypothesis adopted as a basis for this discussion, though the Russian interpretations deviate from those given here on some points.

The scheme as published by Bilibin is more detailed and rigid than suggested by the outline given above. Criticisms have been levelled at it within the Soviet Union and most of these appear to be valid. (See, for example, Radkevich, 1959; Khain & Sheymann, 1960, pp. 181–182). It is evident that many modifications will be necessary to make it fit all orogenic belts. Regardless of obvious weaknesses, this summary is a valuable contribution to the literature of ore deposits and its applicability to mountain systems in other parts of the world should be examined in detail.

It is interesting to note that Bilibin and associates agree with most other writers that igneous activity in the normal case centres first in the basaltic crust and mantle, later, with heavy loading and sinking, in the sedimentary pile, and finally again in the basic rocks beneath.

(D) *Concentration during Stable Platform Modifications*

After stabilization, an orogenic belt becomes part of a continental platform. Platforms, while remarkably stable in comparison with active orogenic belts, are subject to warpings and local faulting. In part these disturbances may be side effects of deformations in active marginal orogenic belts; in part they may be due to differential heating at depth.

Some parts of stable platforms may become involved in deformation of younger adjacent active belts. Rifting and marginal fragmentation may result in the development of orogenic belts within older platforms or the inclusion of continental fragments in younger marginal belts.

Typical intrusions in platforms are diabase dykes. Layered basic intrusives occur in a few places where they may be accompanied by deposits of magmatic sulphides, platinum metals, chromite, titaniferous magnetite, and various hydrothermal deposits. Ultrabasic intrusives may rise to a certain level when internal gas pressures produce explosive eruption, such as in kimberlite pipes and alkaline diatreme complexes, with or without accompanying carbonatites and associated niobium apatite-fluorite deposits. U, Th, Ta, Zr, Hf, and other relatively rare elements may also appear.

In cover rocks, Zn, Pb, Cu, V, and U deposits are found. These deposits present many interesting problems, but they fall outside of the topic selected and will not be discussed further here.

Conclusions

In conclusion I should like to emphasize these points:

(1) Orogenesis has been essential to the formation of most hypogene ore deposits.

(2) If the hypothesis of earth development presented and explored is true, there would have been few ore deposits without orogenesis, for without it there would have been no continents.

(3) The vast quantity of water trapped within sediments in geosynclines, and that contributed from the mantle, passes in large part upward and outward through the complex pile. While it is impossible at present to specify exact processes, the information at hand makes it appear almost certain that such water solutions have played an important part in the formation of most ore deposits.

(4) Many deposits may have been formed by hot water solutions that were not derived from magmas. In the interest of accuracy, therefore, it is desirable to eliminate from the word "hydrothermal", as applied to solutions or ore deposits, all implications that the solutions or deposits have been derived from magmas. If so derived, they may be described as igneous hydrothermal.

(5) Some deposits formed by hot water solutions in early stages in the development of geosynclines have probably been deformed and recrystallized during orogenesis.

(6) Movement of metals as volatiles undoubtedly contributes to the formation of some ore deposits, but its quantitative importance has still to be evaluated.

(7) Diffusion of metals or sulphides in the solid state is an established process that deserves more serious investigation in relation to ore formation.

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Manuscript received September 6, 1962