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VOLCANISM AND METALLOGENESIS[1]

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The last two decades saw great advances in the study of volcanism, ore genesis and their connection, leading to the refining, changing or discarding of many earlier ideas. Our knowledge of volcanic processes and products has expanded greatly. For example, the existence of ultramafic, peridotitic and kimberlitic lavas has come to light. Many petrologists opposed the notion that ultramafic magmas could exist in nature, but the discovery in Siberia of meimechite – olivine crystals in a matrix of ultramafic glass – gave them pause, for this new rock type came "so near to upsetting the case against the existence of a peridotite magma" (Shand 1952). Meimechite is of kimberlitic composition and occurs as lava and tuff and in dykes and sills. The peridotitic komatiites (Viljoen and Viljoen 1969) with their pillow structures and chilled fabrics afford clear evidence of the extrusion in Archean times of ultramafic liquids. Similarly, a number of petrologists held that carbonate magmas could not exist, but carbonatite lavas and tuffs have become known from Uganda, Tanganyika and Zambia (Bailey 1966). Then, though ore geologists had long doubted the existence of ore magmas, this became established fact with the discovery of *magnetite lavas.*

The El Laco volcanic complex in the high Andes of northern Chile contains five large magnetite lava flows, associated with Quaternary andesite-rhyodacite volcanism. They are high-grade iron ore deposits with reserves estimated at 1 billion tons, composed of magnetite with hematite, martite and some apatite and actinolite, in the guise of vesicular lavas which apart from their composition are like basalt flows (Par,k 1961). In addition there occur smaller iron oxide flows,near-surface sills, pyroclastic deposits and hydrothermal veins. The flows crystallized from a volatile-rich iron oxide melt extruded onto the earth's surface. According to some geologists this melt originated through primary magmatic segregation of a magnetite liquid from the parent magma (Rogers 1968). Frutos and Oyarzún (1975), and others, consider the magnetite melt a product of magmatic remobilization of older sedimentary iron oxide deposits, basing themselves on geochemical arguments (low Ti, V and Cr contents). Such an origin would fit the extreme rarity of this kind of deposit, as its generation would depend on volcanism occurring in an area where iron ore deposits are present at a level deep enough for remelting or bulk assimilation by rising magma.

Volcanic processes play a crucial role in the deposition of many types of ore, including mineral deposits of great economic importance, and according to modern metallogenetic conceptions their number is much larger than was formerly admitted. It should be pointed out that the volcanism now taking place on the continents, though spectacular, does not significantly add to the mineral resources of the planet. The volcanogenic ore deposits we know and use owe their existence to different types of vulcanicity.

This has two reasons. First, the volcanism we cannot directly observe, namely submarine vulcanicity, is more important than land volcanism as regards volume and metalliferous potential. Though volcanology used to be the science of terrestrial volcanism, it is now realized that submarine volcanism made a vastly larger contribution to earth history. Second, the two volcanic environments, on land and in the sea, generate types of mineralization that are fundamentally different – at least in my view.

Ore deposits produced by submarine volcanism usually are stratiform and often massive, such as pyritic orebodies, kuroko ores and iron oxide deposits. They were laid down on the seafloor, and though by composition they are sulphidic and oxidic ores, yet they are rocks just as much as the associated silicate sediments and volcanics, together with which they were syngenetically deposited. The oreforming volcanism may be either mafic to intermediate (and often spilitic) or felsic. These syngenetic ore deposits may reach very large dimensions.

Terrestrial volcanism, on the other hand, does not produce stratiform ores of any significance – exceptional occurrences like the Chilean magnetite lavas aside – and the associated mineralizing activities take place principally on a

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subvolcanic level, in the volcano roots. No massive ores are deposited there, but vein ores and disseminated ores, in other words an epigenetic metallization of existing rock. Such ores generally exhibit more variable compositions than do submarine-volcanic deposits, and they are chiefly associated with calcalkaline, dioritic to granitic magmatism. Examples are afforded by the porphyry coppers, molybdenum stockworks, and the epithermal deposits of gold, silver, tin, mercury and antimony.

The assertion that terrestrial volcanism does not exert significant ore-depositing activities on the surface must be qualified. In the first place, volcanogenic mineralizations do occur, to some extent, on the earth's surface. Sulphur, SO_2, chlorides and CO_2 are normal volcanic products, not only in solfataras, fumaroles and thermal springs but also accompanying lava and tuff eruptions. Whether or not ore deposition can take place depends on the availability of metallic elements, and there are several examples of volcanic areas where exhalative sulphidic and other ores are precipitated around active fumaroles or hot springs. During the Vesuvius eruption in 1817 a fissure was filled with a metre of hematite during a ten-day period of ferric chloride and water vapour exhalation (Beyschlag, Krusch and Vogt 1910, p. 122).

Secondly, it may well be that mineralizing processes are at this moment actively generating ore under some volcanoes. The shallow intrusions and hydrothermal convective systems that effected epigenetic metallizations of the porphyry copper type, occurred on a subvolcanic level, very probably underneath active volcanoes. In part of the porphyry copper belt around the Pacific Ocean, in the island arcs in the southwest, geologically very young ore deposits are found. The copper mineralization in the Mount Fubilan porphyry copper (also known as Ok Tedi) of Papua New Guinea shows an isotopic age of 1.1 million years (Page 1975), which is Pleistocene. This very recent mineralization, taken together with the long span of time, since the early Mesozoic, during which porphyry coppers have been forming around the Pacific, makes it probable that epigenetic metallization is taking place even now in the roots of some andesite volcanoes.

Ore deposits are geochemical anomalies, abnormally high local concentrations of elements in the earth's crust. During the three and three quarter billion years we are able to look back into the history of the earth's crust, such anomalous element enrichments have arisen and disappeared time and again. On the earth's surface they suffered erosion and dispersion, to reappear eventually in new concentrations on or within the crust.

The earth may be considered a dynamic system, the sum of the cycles of its constituents, driven by the sun, gravity and the heat from the earth's interior. The cycles of the oreforming elements are composed of enriching and depleting phases. Volcanic processes bring up material from the depths that may be deposited as valuable mineral accumulations on or near the earth's surface, and volcanic heat and chemically active fluids may mobilize dispersed elements in the rocks they traverse and precipitate them elsewhere in a concentrated form as ore deposits. The only process through which new material in quantity, including ore, can be *added* to the earth's surface, not recycled, is volcanism. Those ores that are formed by nonvolcanic processes on the surface originate mostly through dispersion and reconcentration of volcanic and plutonic ores (the latter after denudation), with the sun and gravity supplying energy.

To illustrate these relationships, the largest and most famous gold deposit in the world is the Witwatersrand, an early Middle Precambian sedimentary basin in which gold and uranium-bearing gravels were laid down on extensive deltas. The gold and sulphides in these fossil placers derive from the erosion of the Archean greenstone belts of southern Africa, which constitute the second most important gold-producing geological unit of this area (far behind the Rand, of course). In these belts gold occurs in sulphide-bearing quartz veins that used to be classed as plutonic-katathermal deposits derived from granitic magma. The origin of the gold is now sought in the basaltic and peridotitic komatiites, the distinctive mafic and ultramafic extrusives that are the early manifestations of the greenstone belt volcanism. They are submarine lavas carrying a little finely disseminated gold that was mobilized during later granite intrusion, deformation and metamorphism, to be redeposited as hydrothermal gold veins. The granites played an activating, not a mineralizing role (Saager 1973, Anhaeusser 1976a,b). The Witwatersrand gold thus is ultimately of volcanic origin. Parenthetically, it was the study of these auriferous greenstone belts that brought to light the existence of ultramafic komatiite lavas.

Deciphering the connection between volcanism and metallogenesis is not only an end in itself, in that it satisfies scientific curiosity, but it may also lead to insights ensuring and promoting the continued supply of the minerals our civilization depends on. Now an important aspect of ore-finding is the underlying theoretical basis, that is the concepts that initiate and guide a prospection campaign As Helmholtz put it: nothing is more practical than a good theory. In other words, if one has an idea where to look, what one is searching for will be found sooner. It should be clear by now why ore geologists are interested in volcanism. Even so, it remains difficult enough to find and pinpoint new ore, as any ore geologist knows who has drilled for orebodies.

On the other hand, it evidently is still possible to find important new mineral deposits without having sought after them, by dint of the faculty known as serendipity. Thus the richest kimberlite pipe of South Africa, the Finsch diamond mine, with the unprecedented high grade of 0.165 ppm diamond (1974 production), was discovered in 1960 by Finscham who, it appears, was really looking for asbestos. I hasten to add that a still richer pipe, the Orapa mine (0.184 ppm diamond) in Botswana, was found in 1967 after 12 years of kimberlite prospection. Kimberlite pipes are volcanic diatremes, explosion funnels that have their starting points 2-3 km below the earth's surface, thanks to which we find diamonds, which are mantle minerals, near enough to the surface to be of use to us (it having been said that diamonds are industry's best friend: "Withdraw diamond from heavy industry and virtually all mass-production lines would become paralysed" (Tolansky 1968).

To return to the principle that ore may be found sooner when one has some inkling of where to seek it, it is one of the tasks of ore geology to provide such information, and the increasing realization that volcanism holds the key to many problems of ore formation and distribution has yielded new insights of great value to prospection and exploration. This may be illustrated by practical examples.

The Precambrian volcanogenic massive sulphide deposits in Canada are an important source of metals in the national economy. Very often they are closely associated with coarse felsic pyroclastics. These tuff-breccias were dubbed "mill-rock" (Sangster 1972), to indicate that the coarsest fragmental lithologies invariably outcropped near to the mine mill in sulphide mines, hence adjacent to the orebody. In prospection and exploration for massive sulphides, consequently, the size and vectorial size variation of the fragments in the tuffs associated with this kind of mineralization present a useful criterion for evaluating ore potential.

Another instance: the orebodies in the pyrite mines of Aljustrel, South Portugal – the largest sulphide deposit in the world – are enclosed in schistose porphyries that were found to be volcanic tuffs and could be divided into three mappable units (Schermerhorn and Stanton 1969). When it was further recognized that the sulphide deposits were syngenetic, not epigenetic, and linked to only one of the three tuff formations, an ore-finding criterion was defined that has led to the discovery of important new reserves of cupriferous pyrite beneath a thick Tertiary overburden (Freire d'Andrade and Schermerhorn 1971).

It is seen that the study of volcanic rocks may yield economic results.

Several types of mineral deposits that formerly were interpreted in a different sense are now seen as volcanogenic, and for others a volcanic origin has been proposed. An example is furnished by the immense iron ore deposits of the Kiruna district in northern Sweden. The International Iron Ore Map of Europe (Walther and Zitzmann 1973) marks 823 iron ore occurrences of which a fifth part is being worked. 14 occurrences, among them Kiruna, are classed as hypogene and intrusive-magmatic. These 14 deposits contain 2.5% of the European iron reserves. Six of them are working mines, yielding 10% of the total European iron ore production. Kiirunavaara is either the largest or the second largest underground mine in the world as regards production (San Manuel, Arizona may or may not be number one), producing 17.7 million tonnes of ore in 1974. In the traditional view, still dominant, these very large magnetite-apatite orebodies are magmatic segregations, intrusive into porphyries, forming a special type of mineralization known as "intrusive-magmatic iron ores of the Kiruna type". Still, dissenting opinions have been voiced from time to time. The most recent re-interpretation is by Parak (1975) who proposes an exhalative-sedimentary mode of formation in a volcanic-marine environment, bolstering this contention with impressive arguments.

A number of oreforming elements such as chromium are deposited far below the earth's surface in a plutonic environment, and other elements like aluminium produce surface ores through the action of nonvolcanic processes. Uranium is one of those elements that have not been concentrated by volcanic processes into economic deposits. Still, volcanogenic uranium mineralization does occur. In central Italy (Latium) Quaternary eruption of leucitic volcanics in grabens produced volcano-sedimentary basins that contain supergene uranium ores (Locardi 1975).

Theoretically four factors determine nature and composition of ore deposits:

1. *origin* of the oreforming elements (in a sulphidic ore they are metal and sulphur, and their source need not be the same),
2. *transport* of the ore material to the site of deposition (for instance, hydrothermally, which is to say carried by aqueous fluids activated and driven by heat),
3. *physical-chemical environment* of ore deposition (in the widest sense, from the ambient geology, lithology and mineralogy to pH, Eh, etc.),
4. *mechanism* of ore deposition (for instance, crystallization in open spaces or cumulus segregation in magmas).

When we restrict ourselves to volcanic and subvolcanic ores, the origin of their constituents still poses a major problem; it is particularly difficult to determine whether metals are juvenile or leached from older rock, and when juvenile whether they stem from the mantle or from recycled oceanic or continental crust. The same applies to the volatile constituents except water. The three remaining factors – how are ore components transported to the site of ore-formation, under what circumstances, and how are they deposited – are nowadays fairly well known, thanks to detailed investigations along various lines.

Water, that is water containing significant quantities of dissolved salts, mostly Na, K and Ca chlorides, is the principal agent of transport, and isotopic geology has made it possible to trace the origin of the water in hydrothermal and other mineralizations. This most important result derives from the study of stable isotopes, in this case hydrogen and oxygen. D/H and $0^{18}/0^{16}$ ratios have shown that water deriving from the earth's surface, namely meteoric groundwater on land and seawater under the oceanfloor, plays a very important part in the hydrothermal systems that are set up by magmatic intrusion and extrusion. During deep circulation, groundwater of infiltrating seawater become mixed with juvenile water in extensive subvolcanic hydrothermal convective systems, with magmatic heat furnishing motive power. This meteoric-hydrothermal circulation effected mineralization by transporting metals, sulphur and eventual other components deriving from the magma itself or from leached volcanic rocks and/or country rock.

The problem of the origin of the ore components is linked to the element cycles in the earth's crust. From this point of view the volcanic and subvolcanic ores represent material added to the upper crust. The role of plutonism in ore genesis, that is to say the magmatism that remains far below the surface, has been considerably reduced, compared to older theories. The majority of ore deposits have been formed on the earth's surface or not far below, down to a few kilometres' depth.

While sedimentary ore deposition comprises mechanical or chemical concentration of existing material only, volcanic metallogenesis implies, firstly, a supply of new ore constituents from deeper levels and, secondly, a supply of thermal energy. Activated by this heat, lateral secretion can also come into play.

Keeping this in mind, solving the problem of the origin of volcanic ores means in principle finding an answer to the following questions: where – that is, at what depth and out of what material – did the magma form, and which rocks did it traverse on its way up? This means getting involved with geotectonics.

Let us start with the link between volcanism, metallogenesis and plate tectonics. Two of the three types of plate margins are of importance in this respect because of abundant volcanism along them: they are the *divergent* or constructive and *convergent* or destructive plate junctions, in other words the zones where new plate material is being created and the zones where plates collide and plate material is consumed.

A large part of the economically important volcanic and subvolcanic mineralizations, for example the porphyry coppers, porphyry molybdenums and certain tin, gold and silver deposits, are found along convergent plate margins, either in an ensialic environment as along the west coast of the Americas or in an ensimatic environment as in the island arcs of Southeast Asia and Melanesia. However, the connection with plate tectonics, specifically the subduction mechanism here operating, is still disputed. The characteristic volcanism of these areas is andesitic and their characteristic mineralization is porphyry coppers. If andesites and porphyry coppers are genetically connected with subduction, then the rarity of these rocks and ores in older orogens such as the Hercynian or Precambrian chains might indicate, together with other arguments, that the latter are not plate-tectonic but intra-plate orogens (possibly because the boundaries of Hercynian or Precambrian plates are no longer extant).

The source of the metals in the ores along convergent plate margins is not yet known. Some workers regard them as reactivated older ores, while others think that the metals derive from the melting of subducted oceanic crust, having originated in a divergent plate junction, that is to say, a spreading or ocean ridge. The role of subduction would be to produce the magmas that concentrate and transport the metals, recycling material whose source lies elsewhere, in the environment of plate divergence. Let us take a look at that.

When plate divergence takes place, material from the mantle wells up to form laterally accreting oceanic lithosphere. This occurs along extensive zones in which at first basins form on the surface and during a later stage, when an ocean has been created, ocean ridged (or mid-ocean ridges).

The ocean ridges are the sites of active mafic volcanism, chiefly tholeiitic basalts to spilites produced by partial melting in the upper mantle, and to a lesser extent also alkali basalts stemming from deeper levels in the mantle.

The oceanic lithosphere plates are about 80 km thick and consist of ultramafic mantle material with a 6-8 km cover of oceanic crust. It has been calculated that 3 km^2 of new oceanic lithosphere is created annually by seafloor spreading on the boundaries of the larger plates. With 1.4 km average thickness of the oceanic second layer which consists of mafic volcanics, about 4 km^3 of basalt is produced per year (Chase, Herron and Normark 1975). this is material that is added to the crust, and if the radius of the earth does not change, an equal amount must be removed each year by subduction or some other process. Furthermore, the volcanic heat generated by the formation of oceanic lithosphere equals almost half of the total conductive heat loss at the earth's surface (Chase, Herron and Normark 1975).

The great importance of ocean-ridge volcanism to cycling of material and heat supply in the crust is evident.

These zones of voluminous volcanism are associated with ore deposition. Metalliferous sediments are widespread on and near ocean ridges, and it appears probable on geochemical and other grounds that this marine mineralization originates in juvenile material produced by volcanism, either directly as exhalations or indirectly by hydrothermal activation and leaching of volcanic rocks. The deposits are mostly ferromanganoan calcareous oozes; apart from much Fe and Mn they also contain Cu, Zn and Ni, and furthermore Ba, Pb, Co, V and other metals. Among spreading ridges the East Pacific Rise appears to be especiall rich in metalliferous sediments. Sedimentation rates may be very high (8-10 m in 600,000 years), and the high accumulation rates for elements such as Fe, Mn, Cu and Ba strongly suggest a submarine volcanic origin, as exhalative-sedimentary deposits (Boström 1970, Boström et al. 1974, Boonatti 1975). Massive ferromanganoan or manganoan incrustations also occur.

Hydrothermal circulation of seawater interacting and mingling with juvenile water down to a depth of some kilometres beneath the seabed effects an exchange between the oceanic volcanics and the sea. Submarine hot springs and fumaroles in areas of active volcanism produce metal-rich deposits. Convective hydrothermal circulation takes place, with downward infiltrating and percolating seawater leaching newly formed mafic rocks, to rise again to the seafloor through thermal convection. Seawater and juvenile water provide the carriers for the oreforming elements, volcanism provides thermal energy to heat and thus activate seawater and to drive the resulting hydrothermal solutions, and tectonism along the spreading centres provides the pathways for ore transport by faulting and fracturing the rocks and thus rendering them permeable to circulating solutions.

Volcanism and tectonism along divergent plate junctions are continuous processes, on the geological scale, for as long as seafloor spreading continues and new plate material is created. Hence, mineralization associated with mantle-supplied volcanism should be a continuous process too (unless mantle inhomogeneity would cause depletion of oreforming elements). Such appears to be the case. There is however some difference between the earliest formed deposits, during initial opening, and later oceanic deposits, because the early oreforming processes can draw upon evaporites to produce brines that are much more saline than seawater, hence more effective in the transport of ore components, producing higher metal grades.

Three types of seafloor mineralization may be distinguished: early ore sediments (Red Sea type), late ore sediments (ocean ridge type), and manganese nodules. Though forming the most abundant mineral resources of the ocean floor, the manganese nodules are not discussed here as their origin is still not well known.

The Red Sea is a beginning ocean. It is underlain by tholeiitic basalt lavas and tuffs, new oceanic crust created by magma ascending from the mantle. This process of seafloor spreading drives Africa and Arabia away from each other at a rate of 1-2 cm a year. In the deep axial zone of the Red Sea, graben structures have developed that contain a number of closed basins on the seabed in which hydrothermal metal-rich sediments are being deposited. These deep pools are filled with hot (50-60°) brines rich in metals supplied from springs and fissures on the seafloor. From the brines layered ore muds have been precipitated containing sulphides, principally sphalerite, with pyrite and chalcopyrite, and iron and manganese oxides and hydroxides. The salt in the oreforming brines derives from the widespread underlying Miocene evaporites, dissolved in seawater circulating along faults and fractures (Bäcker and Richter 1973). Volcanism contributed by furnishing heat and, very probably, sulphur and metals, either as exhalations or leached by percolating hot brines. Around these metalliferous basins the normal Red Sea sediments are marls.

The amount of ore produced is considerable: the largest basin, the Atlantis II Deep, is about 15 km long by 5 km wide. Bullard (1974) calculated that the upper 8.5 m of sediment alone in this basin countains 1.1 million tons of copper and 2.9 million tons of zinc.

Metalliferous brines as agents of ore deposition were first discovered fifteen years ago in southeastern California. A 1570 m deep borehole sunk to tap geothermal energy in the Salton Sea area produced a very hot metal-rich brine containing more than 25 wt % dissolved solids. Copper and silver sulphides were precipitated in the discharge pipes (Skinener et al. 1967). According to the isotopic ratios this is a geothermal system in which surface or connate water circulates, becoming heated up to at least 360° C, dissolving salts from evaporites and leaching metals from sedimentary country rock; the sulphur would stem from deeper levels. Note that the stage of ore deposition has not yet been reached here: there is potential for epigenetic meneralization if the metalliferous solutions stay below the surface, and for syngenetic ore deposition on the surface if they (like the Red Sea brines) reach the surface, as seems unlikely for reasons of volume.

The Red Sea type of early-stage mineralization along divergent plate margins is connected with the existence and mobilization of saline sources, namely the evaporites deposited during initial ocean development. Examples are the Mesozoic evaporites occurring along either coast of the Atlantic. No fossil ore deposits of the Red Sea type have yet been discovered, but fossil oceanic crust is not very common either. Moreover, the earliest products of seafloor spreading are also the earliest to suffer subduction and disappear from sight.

During the later stages of ocean development metalliferous sediments are laid down on the spreading ridges. Together with the plate that carries them, the deposits move away from the divergent plate junction where they were generated, and eventually become subducted. According to one theory the copper in the porphyry coppers of the Cordillera and the Andes, and a number of other metals, derive from a mid-ocean ridge in the Pacific Ocean. The oceanic crust containing these metals from the time they were extracted from the mantle, was transported eastwards over a great distance, to be subducted under the American continent. Calcalkaline magma was generated in the subduction zone which in its ascent through the crust carried the metals with it (Sillitoe 1972).

A type of ore that has not yet been found to exist on or near the ocean ridges consists of the massive sulphides that occur as economic deposits associated with ophiolites, and many geologists consider ophiolites to represent fossil ocean ridges. Such orebodies of cupriferous pyrite in an ophiolite setting are known, for instance, from Newfoundland, Italy and Cyprus. They were deposited within or on mafic pillow lavas that are equated with the recent oceanic second layer, meaning that they were formed along a divergent plate margin.

It should be added that volcanic mineralization is not bound to plate margins. Many older ore deposits, from the Archean on, are not connected with plate tectonics. Though a causal link between ophiolite sulphides and divergent junctions appears likely, there exist countless other deposits of massive sulphides not associated with ophiolites that have originated in a different tectonic framework. Such are, for instance, the pyrite bodies associated with felsic tuffs that appear in the Archean greenstone belts, as submarine exhalative-sedimentary ores (Saager 1973). Further, there are massive sulphides that have formed above subduction zones, as in the Philippines. Obviously, the kinds of volcanism that produce massive sulphide deposits can actuate under a variety of tectonic conditions.

If we accept plate tectonics we must realize that *plates comprise two geotectonic environments: plate margins and intraplate areas.* What we call, plate tectonics only applies to plate boundaries. Volcanism takes place both along plate junctions and within plates, that is in plate-tectonic as well as other frameworks. And volcanogenic ore deposition occurs in either geotectonic environment.

Lastly, concerning the connection between volcanism and metallogenesis, it has become clear that though the ore material may (but need not) derive from a very deep source, ore deposition itself is often brought about by deeply infiltrating and circulating surface water, with volcanic heat providing the motive force.

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