PRINCIPLES OF FORMATION OF CHIMNEY-LIKE VENTS IN SHALLOW VOLCANIC ENVIRONMENTS

By W. S. Burbank

Trace Elements Investigations Report 711

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By W. S. Burbank

ABSTRACT

The formation of chimney-like ore bodies in shallow volcanic environments involves a mechanism of transport and exchange of matter and energy in solid rock bodies under conditions of open systems. Similar processes might be expected to become operative as the result of artificial shallow underground explosions.

The evolution of a prototype chimney vent results from escape of vapors from deep, underlying heated ground upward through a vertical fractionating column of rock, condensation in pores and cracks of the shallow rocks causing decomposition of silicate minerals and entrainment of leached substances in fluids propelled by gas pressure. Release of pressure and loss of volatiles cause reprecipitation and partial sealing of systems with a resulting increase in restraining pressure. Condensed solutions bleed through the sealing envelope, mix and react with condensate solutions formed by decomposition of original rock, and eventually cause the filling of spaces with ore minerals.

Any artificial heating of rock to melting can be expected to activate pore reactions in the walls of the energy source and conceivably lead to various heated gases becoming dissolved in natural pore solutions under considerable pressure. Along cracks or fissures these solutions would react with each mineral and tend to migrate upward in converging channels of flow.

INTRODUCTION

The purpose of these investigations of chimney formation in shallow volcanic environments is to explore the principles involved in the mechanism of transport and exchange of matter and energy in solid rock bodies under conditions of open systems. The principles to be discussed may have application in the description of geologic processes applicable to artificial underground explosions. Reasons for believing this to be so are based on the following points:

(1) Natural chimney ore bodies and chimneys of altered and leached rock often occur in shallow volcanic environments under conditions where heated volcanic gases and solutions must have escaped to the surface from underlying bodies of melted rock or from strongly heated rock bodies in the vicinity of bodies of volcanic lava.

(2) The depths involved range from several hundreds of feet to more than a mile beneath the original volcanic surface, and hence these depths are within the range in which artificial energy sources could be emplaced.

(3) The range of structural conditions prevailing in such environments serve to illustrate the effects of various patterns of fracturing and porosity of the rocks on the mechanism of escape of heated solutions and gases.

(4) The effects of differences in composition of the rock environment, such as between limestone and silicate rocks, may be studied by comparison of alteration and degree of leaching by the escaping fluids.

(5) Effects of explosive disruption of the rocks are observable both in chimney and fissure-type vents.

This work is part of a program that the U. S. Geological Survey is conducting in connection with its Investigations of Geologic Processes project on behalf of the Division of Research, U. S. Atomic Energy Commission.

It is concluded from studies of natural phenomena of this kind under a wide range of textural and compositional conditions that the escaping gases and solutions tend to converge upward towards the surface into restricted chimney-like channels, generally steeply inclined, and ranging from a few tens of feet to a thousand or 1,500 feet in diameter. Some of these vents were sources of eruption of lava and fragmental debris, whereas others became the loci of altered rock and bodies of ore. The causes of converging flow of escaping heat and fluids are related to so-called "sealing" effects, which attend the decomposition of rock materials by chemically active vapors and their condensates adsorbed in rock cracks and pores. Sealing may also result from explosive disruption of rocks and injection of clastic debris into open vents, thereby filling and blocking the vents. The intrusion of molten rock into vents may result in its rapid cooling and solidification, a form of sealing more typical of high-temperature environments.

The ground in which such chimney-like channels are most commonly found seems to have possessed original fracture and joint patterns of a symmetrical type. On the other hand, ground subjected to strong linear or irregular patterns of fracturing resulted in forms of eruption and vents of a different aspect. However, once the fissures become sealed by clastic injections or by vein fillings of gangue, the vents again tended to assume chimney-like forms in the partly sealed environment. These tendencies for converging flow thus seem to be a general rule, which may be related to the local restraints imposed by filling of open space. It does not seem to matter whether the open space initially results from the leaching effects of chemically active fluids or whether it results from mechanical effects of deformation. In either case, where sources of heated volatiles exist in the underlying rocks, the space tends to be filled with injected debris or with mineral matter that has been decomposed, transported, and redeposited by altering fluids. This restraining effect on free escape of heated fluids may be illustrated by the evolution of a typical chimney vent (Burbank, 1950; in preparation).

EVOLUTION OF A PROTOTYPE CHIMNEY VENT

The evolution of a typical chimney vent is illustrated by figure 1. Vapors escaping from underlying heated ground through the vertical fractionating column of rock tend to condense in pores and cracks of the shallower rocks causing decomposition of the silicate minerals and the entrainment of leached substances in fluids propelled by gas pressure. Release of pressure and loss of volatiles from solutions tend to cause reprecipitation of the more refractory mineral components in escape vents. Silica and clay minerals fill pores and cracks until certain chimney vents become capped with an envelope of chemically resistant jasperoid. The sealing effect causes building up of restraining pressure in the previously

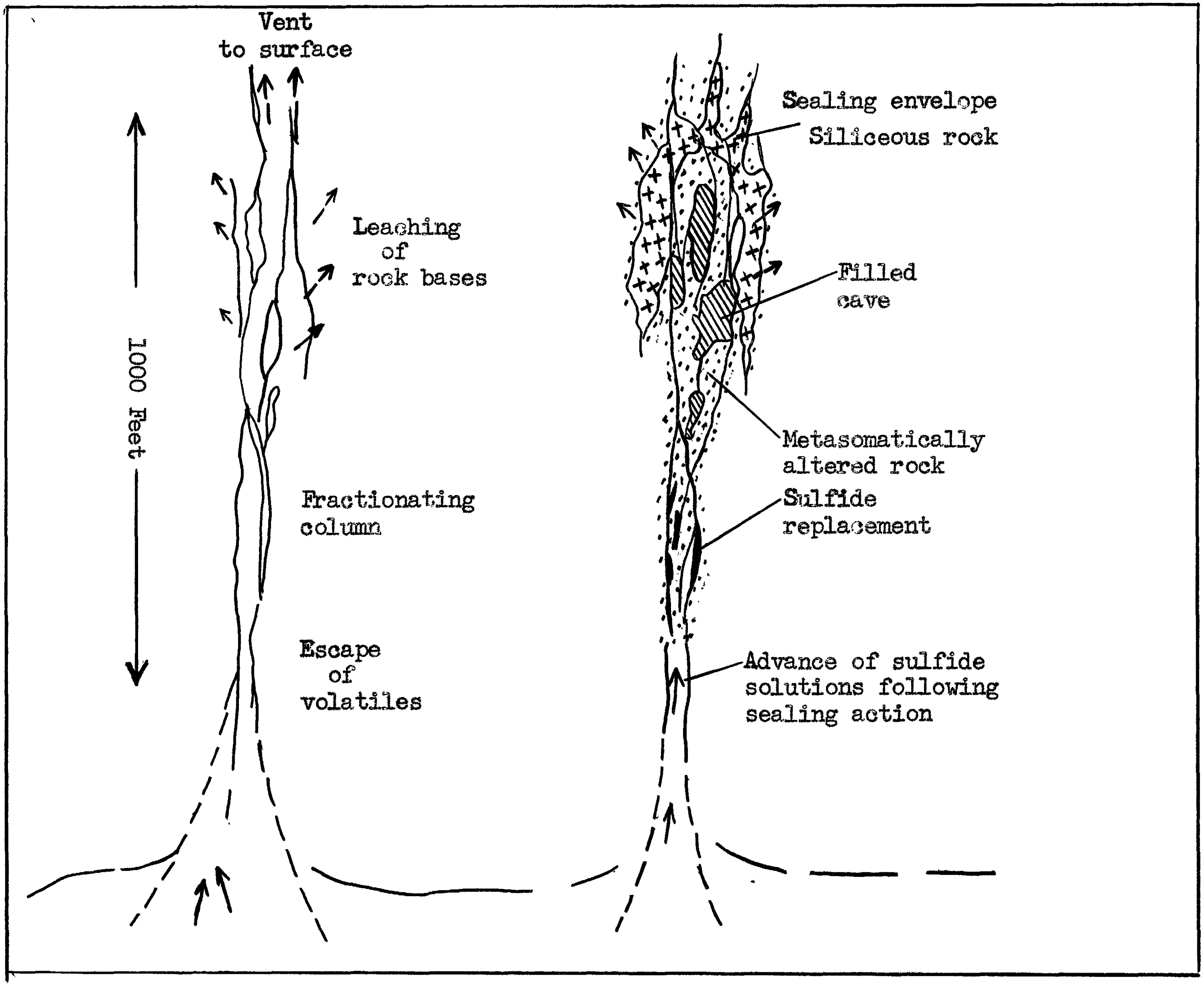

Figure 1.—Diagram of leaching, sealing, and filling stages of chimney column.

leached spaces. Condensed solutions under pressure gradually bleed upward into the spaces where they mix and react with any remaining condensate solutions formed by decomposition of the original rocks. Continued escape of tenuous volatiles through pores of the sealing envelope eventually results in filling of the spaces with ore and gangue minerals.

In the field all gradations are to be found between openings entirely filled with ore and those partly filled or empty. The filled chimney openings may be referred to as activated chimneys in the sense of an action sequence of leaching, sealing, and filling. These sequences of action involve a certain coupling between physical transport and concurrent chemical actions. Unless the actions of sealing are sufficiently effective and fast enough to build up back pressure before the deeper root solutions freeze or become depleted in fluxing volatiles, the stages of action representing advance of sulfide-bearing solutions would not become represented in a particular column. If the advance of the "primary" or deep solutions is thus dependent upon some optimum condition of restraint and its timing, then the several combined actions constitute a coupled series of events controlled by a timing function.

The timing function is controlled in turn by factors of structural, textural, and compositional nature in the local environment. Interacting or coupled processes of this general nature afford a basis for treating the prototype mechanism of the chimney by thermodynamic and kinetic principles of open systems.

REDUCTION OF THE CHIMNEY CYCLE TO FINE-GRAINED ACTIONS

Coupled actions of this kind may extend theoretically to processes of much finer grain than those of the typical chimney. As to size of spaces being filled, all gradations may be observed in the field between larger spaces measurable in cubic yards to spaces of microscopic dimensions. These finer actions become indistinguishable from processes recognized by geologists as metasomatic, by which small particles of minerals grow in the body of host substances. In general, metasomatic processes represent an essentially volume-for-volume substitution by which the crystal lattice of a host substance is destroyed and a new one of different composition is substituted in its place. Such processes may be contrasted with processes like ionic or base exchange, which generally preserve the host lattice. As a result of metasomatic action it is commonly found that only the coarser textures of the rock body, outlines of crystal texture, or included impurities and imperfections of the crystals are preserved. This imperfect preservation or "memory" of a pre-existing texture or structure must generally represent actions taking place in discrete steps above those of molecular dimensions. Also, metasomatic exchanges cannot generally be represented by stoichiometric reaction equations, as in the replacement of silicates or carbonates by sulfides and quartz.

On the premise of this mechanism of replacement the processes are thus not strictly molecular but take place in discrete steps above levels of molecular actions. This view was held by T. Sterry Hunt during the late 1890's, but his views were widely opposed by proponents of molecular metasomatic action.

The steps involved in decomposition and mixing reactions together with concurrent transport may be summarized as follows:

(1) Transport of gaseous or more mobile fluids or ions to surfaces of unsaturated solids by reason of the semipermeable nature of rock bodies or of imperfections of crystal lattices.

(2) Adsorption of mobile fractions on surfaces and in crystal imperfections by chemisorption or by physical attractive forces (van Der Walls effects).

(3) Decomposition of crystal lattices of minerals by bonding action of fluids and surface reactions. The decomposition of a crystal will ordinarily result in an increase in volume of space occupied by its component substances. This may tend to seal space, as will any reprecipitated matter in nearby capillary vents.

(4) Continued corrosion of solids back of the seal may lead to mixing of the adsorbed fluids with advancing primary solutions, owing to slight leakage of seals or to diffusion in capillary spaces. The mixing reactions may lead to a decrease in free energy by the formation of new substances.

(5) If the overall chemical volume changes of mixing and reaction are negative during formation of the metasome and fluid remainder, renewal of this cycle of events will be promoted. Likewise if the difference in capacity for entropy between the reactants and products is positive, conditions will be optimum for spontaneous action.

In general it may be anticipated that the activation stages (1) to (3) will be slow, whereas the mixing and reaction stages will tend to be fast, if the rock minerals are fairly reactive (fig. 2).

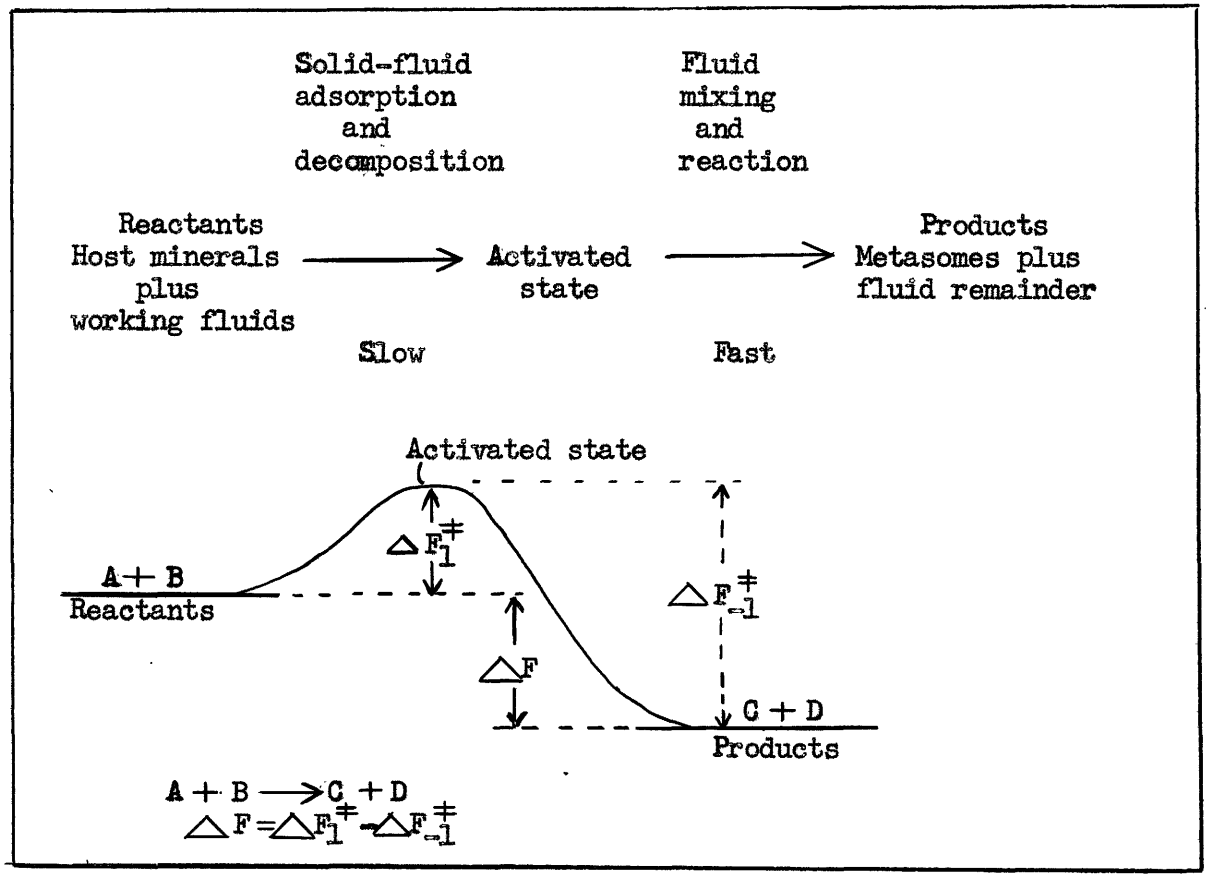

Figure 2.—Illustration of energy relations and rate conditions applied to complex exchange reactions of metasomatic systems.

The thermodynamics of such processes may be treated according to the principles of Eyring's activated complex, by which the system passes periodically to an activated state and thence toward an equilibrium condition. (See also Parlin, Marcus, and Eyring, 1955.) These authors have suggested that this mode of treatment for open systems is much more general than the classical theories of irreversible processes (Denbigh, 1951).

ANALYSIS OF FIELD CONDITIONS INVOLVING COUPLED TRANSPORT AND CHEMICAL EXCHANGE REACTIONS

Within limits between which coupling is effective in reaction and transport actions, it becomes possible to define certain optimum operating conditions that will favor maximum rates of advance of metasomatic fronts. These conditions in turn account for the convergence of flow of the mineralizing solutions into cyclindrical channels at shallow depths.

Metasomatism as defined involves a mixing process during precipitation of the metasome, and this mixing may involve the formation of new minerals not previously existing or possible. When a new mineral of this kind is formed, the process involves a decrease in free energy (or increase in availability of energy) for the complete sequence of replacement actions. It can be illustrated that as sealing action becomes more effective in fine-textured reactive ground, the mixing and reaction processes become more efficient. Hence each repeated sequence of transport and exchange results in increased availability of energy for promoting continued action.

The overall results of metasomatic action in a large body of ground can be considered as an assemblage of innumerable discrete actions that are subject to statistical analysis. The more irreversible are the separate actions (owing to imperfect sealing and loss of energy) the smaller becomes the energy made available to promote continued action. The more nearly "reversible" the overall processes become, the more energy is made available from chemical exchange processes. But in a truly "reversible" process all energy must become consumed in changing composition, and directed motion of matter and energy must cease altogether. Between these extremes of no internal reaction, representing zero chemical efficiency, and reversible processes representing 100 percent chemical efficiency but no motion, there must exist some state of optimum power output. Power output, being measured in rate of energy dissipation per unit time, becomes of significance in coupled processes approaching some steady-state condition as might be represented by an advancing front. The action in such steady-state coupled processes is analogous in principle to coupled electronic systems possessing an internal generator. The restraining action of the sealing process is analogous to an external resistance. Ideally, the power output in such systems under steady-state conditions cannot exceed 50 percent of the "reversible" potential of the system, where the external and internal loads are balanced. In terms of the metasomatic process, if loss of gas and temperature to the surroundings becomes too rapid, the system "freezes," and continued or steady-state action comes to an end. On the other hand, where irreversibility is minimized, the work output becomes vanishingly low in terms of power involved in transport action. These extreme types of action may be illustrated graphically by the diagram of figure 3.

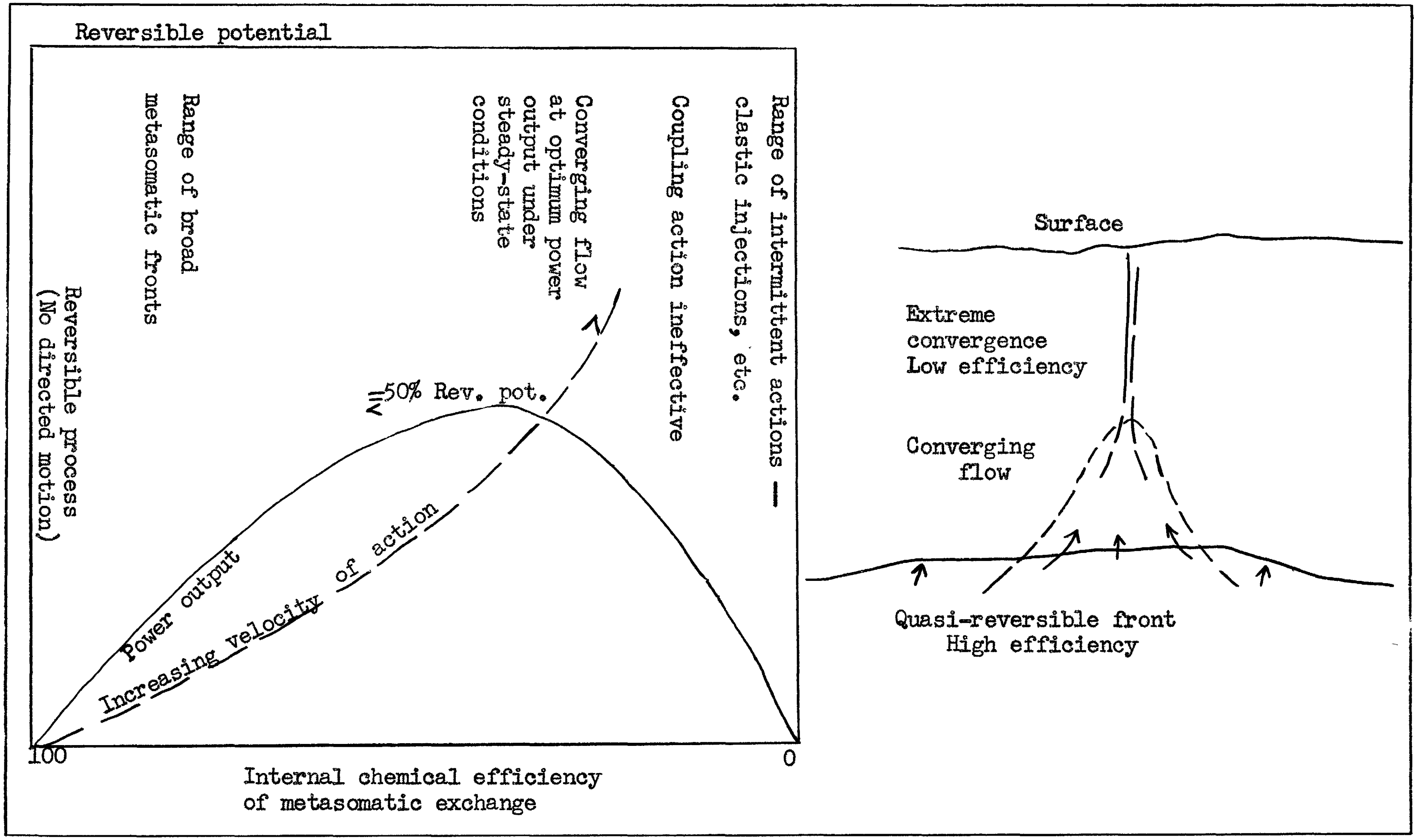

Figure 3.—Relation of power output in terms of available chemical energy for highly efficient metasomatic fronts and fronts of converging flow.

From these general principles it may be concluded that the flow of activating energy and fluids to the metasomatic front will become drained preferentially into those channels affording conditions of "optimum" power output. And by reason of sealing actions in symmetrically fractured ground, the fluids will tend to migrate upward towards the surface in cylindrical chimney-like channels. The chimneys are therefore merely special protuberances of the metasomatic front, which advance faster than the broader and more efficient fronts of deeper ground.

Several special cases may be distinguished depending upon reactiveness of the ground to chemical action, the limits of mechanical stability of the environment to explosive disruption, and the nature of the working fluids involved.

If the spaces do not become sealed in shallow ground, the heated gases and entrained liquids will escape unimpeded to the surface and form fumarolic vents, or these fluids will become entrained in shallow bodies of ground water or meteoric waters. But such continued loss of volatiles from the deeper sources must lead eventually to sealing of ground near the roots of the escape channel.

If the pressures and temperatures are sufficiently high in deep ground, openings produced by fissuring or leaching action may eventually lead to explosive disruption of the walls of the channels. Such eruptions may take the form of clastic dikes or fragmental eruptions from cylindrical vents. Action cannot then be resumed until further accessions of heat and fluids from deeper sources have been supplied.

If the shallow but semipermeable ground is completely unreactive to the escaping gases, or if the ground does not contain pore fluids that may cause reaction by heating effects of the escaping gases, then energy will become drained from the source by gradual escape of the fluids. It appears very unlikely that such conditions would exist normally in natural environments. Most rocks contain pore fluids and, if sufficiently heated, chemical reactions are likely to become activated.

CHEMICAL NATURE OF PORE FLUIDS IN REACTIVE ROCKS

It is generally recognized that the pore fluids of many silicate rocks as well as vein fluids contain mineral salts of the alkalies and alkaline earths as well as some alumina and various minor substances. But as rocks are heated to higher temperatures in the presence of such fluids some of the silicates may become decomposed with the formation of silicate-rich solutions. These solutions are probably of a very complex nature, but many altered rocks in mineralized ground indicate that alkalies have been introduced in the form of potassium- and sodium-bearing silicates like sericite. Solutions such as those of the sodium-silicate-water type studied by Morey and Hesselgesser (1952) could very well be representative of pore solutions in rocks under conditions of moderate temperature and high pressure. Natural solutions may also contain considerable dissolved gases, such as those of sulfur compounds and carbon dioxide. Their effects are evident in many altered rocks. Nothing is known about sulfide-rich solutions of a comparable type, but the fact remains that solutions forming the chimney ores were comparatively rich in sulfides of the heavier metals and very low in gangue content. These very high ratios of sulfides to gangue contrast markedly with the hot spring waters charged with sulfur compounds that emerge from vein fissures in volcanic regions. These waters are very high in gangue content and deposit carbonates, gypsum, and silica, along with minor sulfur or sulfides, and oxides of iron and manganese. Veins formed along the very same channels from which the warmer waters now flow consist mainly of gangues, chiefly silica and carbonates, whereas sulfides rarely constitute more than a few percent of the vein filling.

It appears likely from these relations that the veins were formed from waters very much like those that flow in them today, except that during advances of metasomatic fronts and higher temperature of the deep ground, pore solutions from the deeper rocks bled into the roots of the fissures and enriched the normal meteoric waters with sulfides and silicates of the alkalies. In chimneys, on the other hand, there was little opportunity for the pore solutions to become mixed with abundant meteoric waters of the open fissures. Accordingly, at higher temperatures and pressures the chimney-like vents formed protuberances of the silicate fronts of metasomatic action. With later residual enrichment of the pore solutions with heavier compounds of the sulfur acids and metals, these solutions bled upward into chimney channels to form sulfide ores containing minor gangue components. In general the lighter volatiles rich in carbon dioxide and halogen compounds escaped early along the channel vents. This same sequence is also recorded in the fumarolic vents at the Valley of Ten Thousand Smokes in Alaska (Zies, 1929).

SEQUENCES IN VEIN FISSURES

The effects of repeated fissuring in ground undergoing metasomatic alteration further illustrates various effects of pore solutions and the heating action of deep-seated volcanic eruptions. In the earlier stages of fissure opening, which may take place during deep melting of the rocks, the fissures may become filled with igneous dikes. Following these stages and after cooling and solidification of the shallower volcanic rocks, renewed openings of the fissures may result in clastic injections that represent explosive eruptions of fragmented wall-rock material. Such clastic dikes may be injected thousands of feet above possible sources of the material composing them. This type of eruption evidently represents a stage in which the deeper rocks cut by fissures were highly charged with heated gases and pore fluids. Subsequent reopening of the same fissures often leads to filling of the fissure openings with abundant gangues. The timing of these gangue-rich infiltrations with respect to fissure openings suggests that this action is merely a somewhat more restrained secretion of pore fluids into fissures where they become mixed with meteoric waters from shallower levels. Such gangue infiltrations are generally followed by more restrained and highly fractionated fluids enriched in sulfide minerals. Likewise as the vein opening becomes plugged with gangues, the conditions again favor metasomatic processes of replacement. These general sequences may be repeated several times with renewed fissure openings; but, as temperature and pressure fall, the latest fillings tend to predominate largely in gangue minerals and the sulfide components decrease to mere traces. The latest fillings thus become much like those now found in the older vents of hot springs.

It will be seen that this vein sequence contrasts very markedly with the sequences and nature of filling in chimney deposits, which throughout their formation were sealed from strong mixing with shallower meteoric waters. Likewise the chimneys were not subjected to the repeated opening characteristic of linear tensional fissure systems. To some extent, however, the chimneys reflect minor mixing with the pore fluids of the rocks through which they have passed. As seen, metasomatic action involves mixing in incremental steps, and it is inevitable that pore fluids of the rocks will have an effect upon the composition of solutions converging upward into the chimney channels.

APPLICATION TO PROBLEMS INVOLVING ARTIFICIAL ENERGY SOURCES IN SHALLOWER GROUND

The heating of rocks to temperatures that may involve melting or activation of pore reactions in the walls of an energy source could conceivably lead to various heated gases becoming dissolved in natural pore solutions under considerable pressure. Provided the rocks contain minute guide-lines of flow such as provided by cracks and fissures or open joint planes, these heated solutions could conceivably react with rock minerals and might tend to migrate upward into converging channels of flow. Conditions similar to those of heated fronts of metasomatic action might develop.

The extent to which actions of this kind might develop would depend upon the natural fluid content of the rocks and upon their chemical composition. Limestones are particularly susceptible to the formation of long mantos or nearly horizontal channels that may follow certain limestone layers for many thousands of feet. In some mineralized districts these channels become filled with ore and gangues. Limestone decomposes very readily under action of slightly acidic and heated vapors. Since limestone replacement involves evolution of carbon dioxide, the escape of this gas through the pores of the limestone environment leads to a somewhat greater increase of free space during reaction processes than is involved in replacement of siliceous rocks. The courses of these tubular channels in limestone are often found to be erractic and unpredictable. Solutions rising in vertical chimney-like channels may turn abruptly into inclined or horizontal directions with little indication of the guiding factors. Hence it would be extremely difficult to predict actions in ground of this nature. In silicate rocks, on the other hand, where intersecting steep joint or fracture planes may be the guiding factor (rather than composition), the channels in shallower ground seem generally to form along nearly vertical lines.

It will be noted that the conditions involving artificial explosive actions in deep ground will be different in certain respects from those of natural volcanic environments. In natural environments the rocks had become gradually heated and charged with gases and pore solutions prior to fissuring, whereas this will not generally be true of artificial explosive actions. Hence the formation of clastic injections by internal forces of disruption, as in natural metasomatic environments, would not correspond to those of artificial explosive actions. Fissuring in natural volcanic environments seems generally to result from deep-seated movements of molten rock or to adjustments of shallow bodies to bulging or sinking of large segments of the crust. In general the reopening of fissures, except in very shallow volcanic vents, cannot be directly connected with the internal pressures in rocks caused by fluids and heating action.

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