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SOME ASSOCIATIONS OF ORE MINERALS*

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In the formation of minerals, heat may be considered with respect to (1) the temperature gradient downward from the earth's surface, and (2) the depth which represents an environmental pressure at which the mineral-forming process is active, and (3) the gas or vapor pressure of the phase from which the mineral is depositing.

The relations of these conditions may be treated here under two cases, the first of which will be commented upon before the second is mentioned. In the first case the temperature gradient is so low that at any depth a liquid in the rock has a vapor pressure less than the environmental pressure. The latter pressure has at maximum the pressure of rock load plus the strength of the rocks to resist displacement, and at minimum, the pressure of the superincumbent liquid (+ gas) column plus the capillary or frictional resistance to movement of this column.

Water filling the pores of rocks near the surface extends downward into increasingly hotter rocks. As temperatures increase downward more rock material enters into solution with the water until, at depth, liquid and rock merge and lose their identities in a magma.

If there could be realized a continuous column of liquid grading in concentration from the surface downward to magmatic depths, the difference between the weight of the column and of a similar column of rock would be a measure of the incentive to upward movement of the liquid column. A tendency toward such movement must exist in vertical openings in rocks, but movement is scarcely realized ordinarily on account of frictional resistance, ex-

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cept in larger openings and their direct connections. With respect to suddenly opened fractures, liquid would be potentially explosive. Liquid magma bursting into such a fracture might solidify so as to preserve vesicles formed during the sudden relief of pressure. More hydrous liquids thus intruded would deposit some crystals immediately on the neighboring walls of the fracture and from them slowly build toward the middle a crystalline filling, leaving a residuum increasingly hydrous which would move upward at intervals.

One general mineral association which may be referred to the deeper environment just described[1] is the granite pegmatite. Intrusive bodies of this type have compositions and structures which have led to the conception that they have been derived from a residuum, or from successive residua, of cooling granitic magma. These residua become increasingly hydrous, and enriched in a variety of compounds which, because of high solubility in the liquid, or slight original concentration, have remained in solution until cooled by intrusion as detailed above. Reopening of the fissures after periods of cooling allows successive invasions of liquids, each in general presumably cooler than the preceding, and thus in a state of saturation ready to deposit new compounds, or to dissolve or react with and replace existing minerals. Both Schaller[2] and Hess[3] have presented much evidence for a common replacement sequence—potash, soda, lithia.

Minerals rich in the elements barium, strontium, nickel, cobalt and chromium are almost absent from acid pegmatites, but these elements are known to be present in solid solution in common rock-forming minerals. Therefore their concentration in a residual liquid would be partly prevented.

Copper, zinc and lead are not absent from pegmatites, but pegmatites are not the home of their ores. They are not definitely known as solid solution constituents of common rock-forming minerals. When we have learned, for the oxygen, sulfur and arsenic compounds of the several elements enumerated, something about

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[1] G. W. Morey, *Jour. Geol.*, **32**, 294, 1924, has been led by experimental work to the opinion that critical phenomena do not appear in natural liquids containing an abundance of both water and silicates.

[2] W. T. Schaller, The Genesis of Lithium Pegmatites, *Am. Jour. Sci.*, **10**, 269, 1925; Mineral Replacements in Pegmatites, *Am. Mineralogist*, **12**, 59, 1927.

[3] F. L. Hess, Natural History of Pegmatites, *Eng. Min. Jour.-Press*, **120**, 289, 1925.

the relative solubilities in dry and in highly hydrous rock liquids, then we shall be able to picture more definitely the relative importance of early and late segregation of the elements in a cooling deep-seated magma.

Thus far our attention has been directed to the condition in which the temperature gradient downward is so low that liquid in the rocks has a vapor pressure below the environmental pressure, that is, pressure with respect to temperature is maximal. This condition is favorable for developing at depth a liquid containing abundance of both water and silicates.

Now we may consider that the temperature gradient from the surface is sufficiently steep to produce in the liquid of the rock a vapor pressure higher than the minimum environmental pressure. This is the condition required for the presence of a gas phase. If the temperature gradient is only slightly higher than in the condition previously described the gas phase will develop at intermediate depths, while if the gradient is steep[4] hot gas will fill the pores of the rocks near or at the surface.

Consider a finely brecciated vertical zone of rock of intermediate composition with pores at first filled with water. At a depth of a few thousand feet the mass has been subjected from below to a rapidly increasing temperature, so that the joint blocks are being dissolved to form a hydrous liquid highly concentrated in the constituents of the rock. The vapor pressure of the solution is decreased by concentration and increased by temperature. At some intermediate depth the vapor pressure of the solution exceeds the environmental pressure, and vesicles form in the liquid of the narrow joints. But because of the postulated rising temperature, the rock in the vicinity of the vesicles is getting hotter, therefore the vesicles become extended over a vertical range.[5] At the ends of the range, liquid, gas, and crystals exist in contact, but at intermediate levels, liquid tends to disappear and leave the rock pores filled only with gas. The tendency, however, is only partly rea-

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[4] For some recent studies of hot springs and fumaroles see E. T. Allen and A. L. Day, Steam Wells and Other Thermal Activity at "The Geysers," California. *Carnegie Inst. Publ. No.* **378**, 1927. E. G. Zies, The Valley of Ten Thousand Smokes: I. The Fumarolic Incrustations and their Bearing on Ore Formation. *Nat. Geographic Soc., Contributed Technical Papers, Katmai Series No. 4*, **1929**.

[5] Suppose vesiculation be delayed and supersaturation exist while temperature is rising, then the conditions for vesiculation will be present at levels both above and below the original levels of vesiculation.

lized, for in a mass of rock in which several crystal phases are present in irregular distribution, and in contact with films of liquid, there is a range of temperature at a given pressure at which gas and liquid phases may persist.

When vesicles first form, the liquid just above them has the same temperature and composition as that just below them, but as vesicles elongate vertically the liquid above them has both lower temperature, and lower concentration of rock constituents. As the thickness of the vesicular zone increases, the difference between the upper and the lower liquids increases. Pressure is no longer maintained at substantial equality at the top and the bottom of this gas cushion. The higher temperature at the bottom causes streaming of the gas through pores toward the top, where absorption of the gas by the upper liquid takes place.

Transfer of heat by the streaming gas is much faster than through the intervening blocks of rock. The shapes and sizes of the blocks and pores will thus affect the distribution of gas and liquid in pores and crevices. The interiors of blocks will be enough cooler at first to maintain liquid films into which volatiles from the gas in the crevices will be absorbed. But such films will gradually be displaced by gas as the whole environment gets hotter, and as the volatiles of the liquid evaporate. Thus as the gas cushion grows thicker the rock into which the gas is penetrating is subject to reactions with gas and liquid, some volatiles are absorbed and held in new crystals, others already present in the rock may be given up to the liquid or gas.

Increased volume due to thickening of the gas cushion forces the upper liquid toward the surface through the more open rock crevices. The flow includes liquid which is derived from near the cushion, and which contains volatiles from the lower liquid, or released from the rocks as indicated above. Such a process of leaching, recrystallization and introduction of volatiles may well be considered in attempts to account for the loss of lime, magnesia and soda from, and the introduction of sulfur and copper into, the porphyries of the disseminated copper deposits.