THE

# AMERICAN JOURNAL OF SCIENCE

[FOURTH SERIES.]

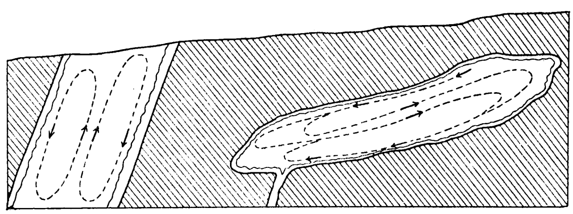
## ART. XXVIII.—*Fractional Crystallization of Rocks*; by GEORGE F. BECKER.

AMONG the phenomena most often appealed to in support of the theory of magmatic segregation or differentiation is the symmetrical arrangement of material in certain dikes and laccolites. This separation seems to me readily explicable in certain cases without resort to the hypothesis of the division of a homogeneous fluid into two or more distinct fluids. I have already called attention to the process in brief terms;* though very well known it has not otherwise been invoked, so far as I am aware, to explain rock differences. If the suggestion has previously been made, it seems time that it should be repeated. If we suppose a dike in cold rock filled with mobile lava which does not overflow, or has ceased to overflow, the mass will be subjected to convection currents, because the liquid near the walls will be cooler than that near the median plane of the dike. A circulation of lava will then take place, the descending flow at the sides being compensated by ascending flow near the central surface. The conditions are roughly represented in the diagram below. If the lava is a homogeneous mixture of two liquids of different fusibility, then the crusts which first form upon the walls will have nearly the same composition as the less fusible partial magma. If one follows mentally a small portion of the liquid in its circulation, it will clearly deposit at each of its early contacts with the growing

* This Journal, vol. iii, 1897, p. 39.

walls a part of its less fusible component, and at each completed revolution it will have a different composition. This composition will always tend towards that which represents the most fusible mixture of the component compounds. When this composition is attained, the magma will no longer undergo change by circulation and partial solidification; and the residual mass will gradually solidify as a uniform material. Unless then the injected magma happened to be a mixture of maximum fusibility, the dike would exhibit a gradation in composition from the sides towards the center. In a very narrow dike solidification might take place before an opportunity was afforded for the complete elimination of the less fusible material; while in wide dikes solidified from mobile magmas one might expect the central sheet to approximate to maximum fusibility.

It is evident that the process of solidification in a laccolite closely resembles that in a dike, particularly if the section of greatest area is not absolutely horizontal. Convection will then be set up and solidification from the walls must tend to the evolution of a residuum of extreme fusibility.



Convection in dikes and laccolites.

The process sketched is one of the most familiar in chemistry and is usually known as fractional crystallization. It has been employed in the purification of compounds ever since chemistry was pursued, and indeed before; for the preparation of salt from sea water or brine depends upon it. It can be and has been employed also to strengthen solutions. A familiar instance is the freezing of weak alcoholic liquids. A bottle of wine or a barrel of cider exposed to a low temperature deposits nearly pure ice on the walls, while a stronger liquor may be tapped from the center. If a still lower temperature were applied the central and more fusible portion would also solidify. Such a mass would be, so far as I can see, a very perfect analogue to a laccolite. A similar concentration is effected in the Pattinson desilverization process.

Though fractional crystallization is said to have been familiar to Parcelsus and even to Aristotle, the process has been studied most thoroughly by Mr. F. Guthrie.* As is well known, he

* Phil. Mag. (5), vol. xvii, 1884, p. 462.

names the property of maximum fusibility in mixtures eutexia and the bodies which exhibit this property he calls eutectic. The phenomena are not always so simple as is supposed in the illustration given above, especially when masses, as they approach the temperature of solidification, divide into immiscible fractions. In such cases one has to do with two or more eutectic mixtures. Supersaturation may also intervene to complicate matters and change of pressure probably influences the composition of the eutectics.* Thus it is at least conceivable that very complicated cases should arise, while if the process plays a part in lithogenesis the simplest case is probably the most frequent.

The fractional crystallization process depends essentially upon convection currents. That it is not incompatible with convection is clear, while convection is the mortal enemy of any process of separation involving molecular flow. The only function of diffusion in this case would be to preserve the homogeneity of the residual fluid or mother liquor, so that the eutectic state could not be attained by any sensible part of the fluid until the whole mother liquor was reduced to this condition.

The effect of the solidification of crusts on the walls of a dike or laccolite is to liberate heat. This liberation does not raise the temperature, for otherwise the crusts would remelt; but the liberated heat must be conducted through the walls before the dike as a whole can congeal, and it therefore delays the process of solidification, giving additional time for the evolution of an eutectic magma.

There appear to be some conditions under which eutectic action could not be expected. Unless an intrusive rock possesses considerable mobility, chilling would proceed more rapidly than convection, and eutectic separation would be very imperfect if not completely obscured. Viscosity of the mass would also interfere seriously with the uniformity of composition of the mother liquor. If the mass cooled very slowly indeed, this uniformity might be established even in a very viscous mass; but very slow cooling would also mean very slight convection. In viscous lavas, therefore, fractional crystallization is not very probable. There is seemingly no exact way of defining the degree of viscosity compatible with fractional crystallization, but enough mobility must certainly be present to maintain uniformity in the melted mass when diffusion and convection coöperate. I have shown that, in some solutions at any rate (all for which I could find appropriate experimental data) diffusivity is inversely as the square of viscosity.† If any such law holds for magmas, a moderate amount

* Ostwald, Allgem. Chemie, vol. i, 1891, p. 1027.
† This Journal, vol. iii, 1897, p. 284.

of viscosity would preclude the formation of eutectic mother liquors.

Eutectic mixtures by definition would have no tendency to fractional crystallization however fluid they might be and however strong the convection currents. Where dikes represent the last remnant of magma in a solidifying mass, one would expect to find them of eutectic composition, as has been pointed out by Mr. J. J. H. Teall.* Convection being needful to fractional crystallization, it would seem essential that the cooling magma should be surrounded by masses of a lower temperature.† In the case of dikes this condition is ordinarily fulfilled. On the other hand, if laccolites ever form and solidify without ejection at great depths and in contact with rocks of high temperature, it seems improbable that convection and partial crystallization would come in play to a sensible extent.

It is difficult to see how so simple and natural a process of solidification as fractional crystallization can fail to be carried out in at least some rocks. Dikes and laccolites assuredly chill from their external surfaces and (barring either an original eutectic composition or insuperable viscosity) there seems no way of avoiding fractional crystallization. It has often been noticed that there is an accord between the order of consolidation of minerals as observed under the microscope and the arrangement of minerals in dikes, the compounds of early secondary crystallization being most abundant near the walls. This is of course what would be expected from a process of fractional crystallization. Observation would no doubt throw further light on the composition of eutectic rock mixtures. Narrow stringers from a so-called "basic" dike would represent the mean composition at the time they were filled; and unless the composition of the magma changed during flow, the stringers should represent the average dike rock. The middle portion of the dike, on the other hand, should tend to display eutexia. Dikes which are homogeneous ought to be eutectic. Many experiments have already been made on eutectic mixtures of salt both in the dry and the wet way. It does not seem impossible that experiments on eutectic mixtures of rock components should give results of an approximation sufficient for the purposes of lithology.

Few, I believe, will maintain that any great progress has been made in explaining the theory of the segregation of magmas into partial magmas. Mr. H. Bäckström,‡ for example,

* British Petrography, 1888, p. 401.

† Dr. W. F. Hillebrand reminds me that the changes in density of the mother liquor during crystallization will of themselves induce convection, though perhaps not powerful currents.

‡ Jour. of Geol., vol. i, 1893, p. 773.

denies the applicability of the Ludwig-Soret law. In this he seems to me correct, but I fail to see that he gives adequate reasons for the rejection. He resorts to the separation of magmas into immiscible fractions for a working hypothesis, but without showing how the necessary variations of temperature are to be accounted for. Mr. Alfred Harker* also regards the Ludwig-Soret law as inapplicable to magmatic segregation, which he seeks to explain by the molecular flow attendant upon crystallization. The maximum rate of molecular flow is thus provided for, but I have shown that even under these most favorable circumstances the time required for the separation of considerable masses of material from one another would be practically infinite in any solutions of known properties. Mr. Michel-Lévy again, whose researches in physics give his opinions on the segregation of magmas the greatest weight, has reviewed the hypotheses of Messrs. Brögger and Iddings. He points out the enormous time required for the process and, as others have done, the impeding influence of viscosity. The results of experiment, he thinks, are more favorable to the old theory of superposition of magmas in the order of decreasing density. He finds many objections both to the hypotheses and to the evidence in their favor, and the only point which he regards as certain is that there are some consanguineous rocks. These, he thinks, probably came from a reservoir in which the initial magma has undergone only such modifications as were consistent with the preservation of its distinct individuality.† It seems needless to enlarge further on the unsatisfactory condition of the theory of differentiation.

On the other hand, the simple principle of fractional crystallization, which is the very opposite of magmatic differentiation, is in most respects thoroughly well understood, it is known to be practicable by hundreds of thousands of experiments, many of them on a fairly large scale, and its action is so rapid as to bring about in days diversities of composition which it would take centuries to bring about by processes depending on molecular flow. In dikes and laccolites of mobile lavas fractional crystallization seems inevitable, while the convection attending it is inconsistent with segregation by molecular flow. Surely it is worth the while of lithologists to consider in how far differences in such rocks as are beyond a doubt genetically connected can be accounted for by a process which is almost inseparable from consolidation.

Washington, D. C., June, 1897.

* Quart. Jour. Geol. Soc. London, vol. l, 1894, p. 311.

† Bull. Soc. Geol. de France (3), vol. xxiv, 1896, p. 123. I should have been glad to reinforce some of the reasoning in a paper printed in this Journal, vol. iii, p. 21, by reference to Mr. Michel-Lévy's paper cited above; but it did not come under my eyes in time.