THE WATER CONTENT OF MAGMAS.[1]

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ABSTRACT.

Consideration of the analyses of "average igneous rocks" of the several types leads to the conclusion that the average magma certainly contains not less than 1.5 per cent of water and probably not less than two per cent. These are minimum figures appropriate to shallow zones in the earth.

Volcanic phenomena appear to indicate high water content of the underlying magma, and migmatization and granitization, together with the lower-grade metamorphic processes such as chloritization, saussuritization, and albitization, show that the primary water content of the siliceous magmas was much greater than would be deduced from the analyses of the crystalline rocks. These features also indicate that the water content of obsidian, which might be taken as prima facie evidence of the primary water content of the magmas, is much lower than is appropriate to the deeper levels of the crust.

It is at present impossible to fix quantitative values for the water content of the primary magmas, but values of four per cent for basalts and perhaps as much as eight per cent for the granitic magmas at depth seem much more in keeping with the geologic data than the much lower estimates that have been made.

Such figures appear to be consistent with the values that might be derived on the assumption that the hydrosphere has arisen from the differentiation of the basaltic shell of the earth.

The influence of the water content of magmas on their differentiation and the evolution of the igneous rocks has long been a matter of debate. Many geologists have attributed a large influence to the water content of magmas; others have declared the influence to be slight. The actual content of water in magmas has received little attention and in the nature of things is difficult or impossible to measure accurately. Bowen, whose argument is outlined below, although not committing himself to definite figures, implies that only 0.5 per cent water is normally present in basaltic magma[2] and that one or two per cent is normal in granitic magmas.[3]

There are many geologic and volcanologic evidences that go to show that the water content of both basaltic and granitic magmas is considerably greater than these figures would connote.

Obviously the most direct approach to the problem of the

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[2] Bowen, N. L.: The evolution of the igneous rocks, p. 301, Princeton, 1928.

[3] Idem, p. 297.

original water content of magmas is given by analyses of rocks formed by the crystallization of the magmas. We can be reasonably confident that the quantities present in fresh rocks are minimum quantities for the parent magma, for it is inconceivable that a magma can consolidate in any geologic environment without some losses of volatile matter. Accordingly, the water content of the average igneous rock in the crust of the earth, as computed by Clarke and Washington (from the "superior" analyses only), should represent the minimum amount. This amount is 1.15 per cent (H_2O+).[4] As is customary, the water given off below 105° is regarded as nonmagmatic; throughout this paper "water" means "H_2O+."

According to the theory of differentiation through crystallization and from general geologic evidence, the primary water content of a magma should be concentrated into the more siliceous differentiates. On the average, therefore, the granites and rhyolites should carry more water than the gabbros, norites, diabases, and basalts.

Daly's computed averages of the several rock types[5] show for gabbro 1.45 per cent of water and for diabase 1.89 per cent. The average norite, despite the fact that assimilation of hydrous shale and slate is often cited as the factor that gives the stamp to this class of rocks, carries only 0.79 per cent of water. However, the average granite has only 0.84 per cent of water; that is, less than half the content of the average diabase and less than 60 per cent of that of the average gabbro. Similarly, the average plateau basalt, with 1.80 per cent of water, is more hydrous than the average rhyolite, with 1.47 per cent. The average content of all basalts is 1.62 per cent of water. These figures fail to support the idea of concentration of water in the siliceous rocks.

However, these figures do appear to show a rough correlation between the geologic setting of a given igneous rock and its water content. Thus, gabbro is more hydrous than granite, in conformity to the general occurrence of gabbro in deeper-seated rocks than the average granite. The average plateau basalt is more hydrous than the average of all basalts, probably corresponding to the general belief that the plateau basalts are more directly derived from deep earth zones than other basalts

[4] Clarke, F. W., and Washington, H. S.: The composition of the earth's crust: U. S. Geol. Survey Prof. Paper 127, p. 16, 1924.

[5] Daly, R. A.: Igneous rocks and the depths of the earth, pp. 9, 17, New York, 1933.

and hence have not lost as much volatile matter on their way to the surface. Both the plutonic rocks, however, are less hydrous than their effusive correlatives, probably because of partial quenching of the extrusive rocks.

Quenching does not seem to afford a complete explanation for this anomaly, however, for the obsidians are much poorer in water, on the average, than the rhyolites. Bowen, indeed, has argued that the most dependable clue to the primary water content of magmas is furnished by their quenched products, the glasses.[6] The low water content of the average obsidian (less than 1 per cent) is notable in this connection. Owing to the rate of thermal conduction being so much higher than the rate of molecular diffusion in silicate melts, such losses as would occur at high levels must, in Bowen's view, be recorded by vesiculation. The present low water content of glassy rocks that are not notably vesicular, he thinks, must be regarded as representative of the magma from which the obsidian was derived.

This line of reasoning appears most logical, but the evidence of a much higher water content in the crystalline rocks than in the average obsidian, together with other geologic evidence of higher water content, is so strong that I am inclined to seek another explanation for the poverty of the obsidians in water. It seems entirely conceivable that a magma column standing at high levels in the crust may lose a large part of its water by vesiculation, and then, during extrusion, may have its temperature raised by exothermic chemical reactions in the lava or by "porous plug" expansion. The increased fluidity brought about by this increase in temperature might give opportunity for the bubbles to escape or to be stretched into minute threads and for the glass to be annealed and the evidence of the presence of bubbles to be destroyed. Thus the loss of volatile matter at an earlier stage would be concealed. Indeed, the very presence of water would promote crystallization, so that more water-poor magmas would tend to form obsidians than would water-rich magmas.

This or some analogous process seems to be necessary to account for the low water content of the obsidians. The laboratory investigations seem to indicate that water is concentrated, to use Bowen's phrase, by a process of "silicate transfer of the volatiles," into the siliceous fraction of a crystallizing magma. If rhyolitic magma is to be taken as a dif-

[6] Bowen, N. L.: op. cit., pp. 296-297.

ferentiation product of basaltic magma it must thus have originally had a higher water content than the parental basalt; but the original basaltic magma, as shown by the impoverished crystallized residuum, apparently contained at least two per cent of water. As the rhyolites contain, on the average, roughly the same amounts of water as the basalts, or even somewhat less, they support Phemister's conclusion[7] that this equivalence in water content is not due to any effect of magmatic differentiation but to the probability that both basaltic and rhyolitic magmas stood at high levels in the crust long enough for their water content to be controlled by the pressure rather than by the position in the differentiation series.

On several grounds then, we seem to be justified in assuming that the fresh crystallized and glassy rocks both give minimum values for the water content of the parental magma. The difficulties in the way of obtaining quantitative estimates of the real values are, however, great and at present insuperable. One way of getting an estimate has been outlined by Phemister.[8] He assumed an analogy between the relations in natural magmas and those in the system $K_2SiO_3 : SiO_2 : H_2O$, studied by Morey and Fenner. From the assumption that the water content of the average basalt is that appropriate to equilibrium under a pressure of three atmospheres and that equilibrium is maintained to great depths, he deduced that the higher pressure at 18,000 feet would require about five per cent of water in the basaltic magma, if the natural system corresponds with the artificial one. This sort of extrapolation from so little basis cannot be regarded as a very dependable estimate, but it may be worth while to point out that Perret[9] concluded, from observations, that the correspondence between barometric pressure and rate of gas evolution at Vesuvius (a subsiliceous volcano) in 1906 indicated a nearly perfect equilibrium between gas pressure and atmospheric pressure and that gas content must greatly increase with depth in the volcanic neck.

The volcanologic and geologic evidences of large losses of volatile matter strongly support such a view as an explanation of the discrepancy between the water content of lavas and obsidians.

[7] Phemister, T. C.: The rôle of water in basaltic magma: Min. pet. Mitt., Band 45, pp. 32-33, 1934.

[8] Phemister, T. C.: op. cit., pp. 23-27.

[9] Perret, F. A.: The Vesuvius eruption of 1906: Carnegie Inst., Washington, Pub. 339, p. 60, 1924.

The discharge of gas (largely steam) at Vesuvius was so enormous as to lead Perret[10] to conclude that "the eruptive element, par excellence, is gas," "the main function of the magmatic reservoir is the evolution and accumulation of gas," and the magma column possesses latent explosiveness "proportionate to its depth." Similar conclusions were drawn by Perret from the conditions at Stromboli.[11] It was, of course, impossible to compute the volume of gas emitted during the eruption of Vesuvius, but Perret states that for fully 12 hours the gas issued from the throat of the volcano, 400 meters in diameter, with such velocity that at a height of 12 kilometers the edge of the column was only 2.5 kilometers from the volcanic axis and the total volume emitted would "truly stagger the imagination."

The total volume of ash, estimated by Sabatini[12] at 0.21 cubic kilometer, must have represented only a vanishingly small fraction of the gas volume at atmospheric pressure because much of the gas, when ejected, was free of solid material. Using the figures given by Lacroix,[13] the mechanical equivalent of heat of 1 kg. of water at 1,200° C. is sufficient to raise 391 kg. against gravity for 1 kilometer. If the ash had a specific gravity of 2.5 and if it was elevated to an average distance of 10 kilometers, the emission of 2.5 per cent of water from the ash would be required to bring about this effect. This estimate assumes that, on the average, the ash was raised to the height stated, which is probably an exaggeration, but as it also assumes that all the energy of the water was converted to mechanical energy and further that the energy was all used to lift the ash, there can be no question that the estimate is very conservative. Probably, to judge from Perret's descriptions, the eruption was very wasteful of mechanical energy, and the figure given must be multiplied by a considerable factor to give a true idea of the amount of water evolved. Doubtless the water was in large part derived from a great depth in the throat of the volcano, but the vesicles formed in the throat would leave no traces of this evolution after a period of quiescence.

The practically continuous evolution of gas at Kilauea, which has led Daly to the postulate of "two-phase convection" as a

[10] Perret, F. A.: op. cit., pp. 44-47, 58, 66-69.
[11] Perret, F. A.: op. cit., p. 72.
[12] Perret, F. A.: op. cit., p. 89. (Note by H. S. Washington.)
[13] Lacroix, A.: La Montagne Pelée et ses éruptions, p. 359, Paris, 1904.

means of maintaining volcanic activity,[14] and which has been stressed by many other investigators,[15] is apparently not particularly recorded in the textures of the pahoehoe lava of this vent.[16] Yet vast quantities of gas must be emitted in proportion to the lava emanating from the volcano, for the evolution of gas is essentially continuous and the outbursts of lava are periodic only. Thus, even in basaltic volcanoes, in which pyroclastic material is generally subordinate to lavas and indeed is in many almost lacking, there is considerable loss of volatile matter. How much greater loss occurs in andesitic and rhyolitic volcanoes is impossible to measure accurately, but the very large proportion of pyroclastic ejecta furnished by these volcanoes is ample evidence that the water content of the rocks is only a part, and perhaps a small part, of the water content of the parental magma.

Lacroix points out[17] that much of the volcanic edifice of Pelée (and many other siliceous volcanoes) is built of ejecta like those of the observed nuées ardentes. Although it is true that the pelean lavas are porphyritic, and hence that the explosive power may be due to the "second boiling point effect," the Krakatoa eruption, of even greater violence, produced ejecta that were almost wholly glassy.[18] In the Krakatoa magma, then, we appear to be dealing with primary water concentration high enough to have blown much material to heights of 40 miles. The gas concentration must have occurred prior to the onset of crystallization, for evidences of resorption are not prominent in the ejecta.

The effect of pressure in increasing the solubility of water in magmas has been stressed by Daly[19] and is borne out strikingly by the work of Goranson,[20] who has shown that at a temperature of 900° a glass made of Stone Mountain granite would dissolve about four per cent of water at pressures of 500 bars, about 5.5 per cent of water at 1,000 bars, and over eight per cent of water

[14] Daly, R. A.: Igneous rocks and the depths of the earth, pp. 366-372, New York, 1933.

[15] Perret, F. A.: The circulatory system in the Halemaumau lava lake during the summer of 1911: This Journal, Vol. 35, pp. 337-349, 1913.

[16] Washington, H. S.: The formation of aa and pahoehoe: This Journal, Vol. 6, pp. 409-423, 1923.

[17] Lacroix, A.: op. cit., p. 649.

[18] Judd, J. W.: The eruption of Krakatoa: Report of the Krakatoa Committee of the Royal Society, pp. 36-38, London, 1888.

[19] Daly, R. A.: Igneous rocks and the depths of the earth, pp. 364-372, New York, 1933.

[20] Goranson, R. W.: The solubility of water in granite magmas: This Journal, Vol. 22, p. 494, 1931.

at 2,000 bars, corresponding to depths in the crust of about 2, 4, and 7½ kilometers respectively. Beyond this point the solubility of water was only slightly increased by pressure, rising to less than 9.5 per cent at 4,000 bars (15 km.).

The geologic evidence is compelling, it seems to me, that the water content of many granitic magmas is of the general order of these figures. It is true that the pyrometasomatic effects of shallow intrusive masses are commonly produced at late stages in their crystallization and may be largely explained by the action of waters given off by the "second boiling point" effect: that is, the vapor pressure of the solution, which may have been moderate because of low water content at the time of emplacement, has been built up by crystallization of anhydrous phases to large figures as the water was concentrated in the rest of the magma. Such a conclusion as to the stage at which water is given off from a magma, however, can hardly be drawn from the migmatite zones surrounding the concordant intrusives, and there is much evidence that goes to show that even intrusives at a high level in the crust are commonly very rich, relatively and absolutely, in water.

The migmatite zones, which in some places surround granitic intrusives but elsewhere cannot be definitely referred to any particular intrusive mass, give strong geologic evidence of transfer of water on a very large scale. Where the parental granitizing mass is exposed, there is characteristically a complete gradation from intrusive to host rock, without hornfels zones or other signs of discontinuity. Although part of the migmatization is a true injection of magma, the migmatites also show evidences of replacement on a gigantic scale. Material has been transferred from magma that is still in the magma stage, as shown by its structure, to the host rocks in huge amount. The evidence that this replacement is by hydrous solutions is in many places compelling. Porphyroblasts set in matrices that retain undisturbed residual structure, alteration of feldspar composition without change of form, pseudomorphism of older minerals, and similar features demonstrate that the transfer was metasomatic.

The bulk composition of large volumes of the phyllites of the Stavanger region has been shown by Goldschmidt[21] to have changed during metamorphism by addition of more than

[21] Goldschmidt, V. M.: Die Injektionsmetamorphose im Stavanger-Gebiete: Vidensk. selsk. Kristiania Skr., 1920, Mat.-Nat. Kl., 2. Bind, no. 2, pp. 108-118, 1921.

one per cent of soda (in places 2.8 per cent), 1.7 to 3.1 per cent of lime, and as much as 26 per cent of SiO_2. That the water necessary to hold this material in solution was several times as much as the mass of the material transferred seems obvious. When it is borne in mind that cubic miles of rocks have been so altered, the amount of water required is seen to be enormous.

The Stavanger region is certainly not exceptional among areas of intense metamorphism either in the transfer of material per unit volume or in the total volume of rocks affected. Sederholm has estimated that 21.8 per cent of the observable rocks in Finland are migmatites.[22] In addition, large volumes of rocks that are called schists, phyllites, or slates have undergone less transfer of material than the true migmatites but have nevertheless been penetrated in many places by large amounts of metamorphosing solutions of magmatic source.

Tranfer of material on a regional scale has been widely recognized in many other places; an example has been recently described in detail by Balk and Barth,[23] who convincingly demonstrate the transfer in hydrous solutions of material adequate to alter by many per cent the bulk composition of the rocks of many square miles in southeastern New York. In this connection should be mentioned comparable studies by Fenner[24] in New Jersey, Lacroix[25] in the Pyrenees, and Quirke[26] in the Lake Huron region.

Similar transfer of material on a less impressive but still very notable scale is recognizable in the peripheral zones of the migmatites, even where the metamorphic grade is low enough for the green schist facies. As these rocks form a continuous series with the ultrametamorphics and show bulk compositions definitely changed in smaller yet notable amounts, the permeating solutions must, as pointed out by Barth,[27] be referred to a magmatic source. All the water might be assumed to have been indigenous in the sediments prior to

[22] Sederholm, J. J.: The average composition of the earth's crust in Finland: Comm. géol. Finlande Bull. 70, p. 4, 1925.

[23] Balk, Robert, and Barth, T. F. W.: Structural and petrologic studies in Dutchess County, N. Y.: Geol. Soc. America Bull., Vol. 47, pp. 685-850, 1936.

[24] Fenner, C. N.: The mode of formation of certain gneisses in the Highlands of New Jersey: Jour. Geology, Vol. 22, pp. 594-612, 694-702, 1914.

[25] Lacroix, A.: Le granite des Pyrénées et ses phénomènes de contact: Services carte géol., France, Bull. 71, 1900.

[26] Quirke, T. T.: Killarney gneisses and migmatites: Geol. Soc. America Bull., Vol. 39, pp. 753-770, 1927.

[27] Balk, Robert, and Barth, T. F. W.: op. cit., p. 830.

metamorphism, but the variation in chemistry of the altered rocks is so systematic with respect to the intrusive masses that the silica, alkalies, and, in places, magnesia transferred must be largely referred to the magma. As it is certain that silica and soda, for example, have been added in large amounts at many contact zones and in progressively lesser amounts away from them, it seems impossible that any considerable part of the silica enrichment of the feebly metamorphic zones can be due simply to metamorphic diffusion through the medium of water indigenous to the slates, phyllites, and schists. And if it be assumed, for example, that the feeble silicification of the exterior zones is due to transfer of material from rocks nearer the intrusive by indigenous water, the impoverishment of the inner zones thereby produced has been more than outweighed by the contributions from the magma.

In the nature of things it is impossible to set quantitative limits to the water involved in this regional metasomatism. Some of the contributions in the inner zones were, of course, truly magmatic, but the evidence that much of the material was moved in extremely tenuous solutions is very strong, and as literally cubic miles of rock have been changed several per cent in bulk composition, the water given off from the magma must also be measured in cubic miles.

The volume of magma supplying these contributions can also not be determined. But if, in random sections of the deeper zones, such as are represented in the Fennoscandian Shield, 52 per cent of granite is exposed, as estimated by Sederholm, together with nearly 22 per cent of migmatite, there must be postulated very deep granitic hearths indeed to yield enough water for the migmatization, unless generous estimates are made of the primary water content. For example, if the bulk composition of the migmatites has been changed by only ten per cent (certainly a moderate estimate), the hydrous solutions responsible must have amounted to several times the weight of the solutes transferred. On the arbitrary assumption that the solutions carried 20 per cent of dissolved material, all of which was deposited in the recognized migmatites, and on the further assumption that equal depths of migmatite and granite were involved in the exchange, there must have been a concentration of 20 per cent of water in the magma. This amount is surely much too high, for no doubt the migmatites are not formed at depths as great as the bottom of the granites, though they have not shown any signs of dying out at the exposed levels of the crust. But this crude estimate does show that to obtain values as low as two per cent for the primary water content of the granitic magma a depth of granite ten times that of the migmatites in Finland must be postulated. Surely a more reasonable postulate on geologic grounds would be a water content of six to eight per cent for the granitic magmas.

The more moderate metamorphism produced by the crosscutting igneous masses apparently requires far less primary water in the magma. But the crosscutting masses lie in the zone of fracture, and it is entirely conceivable that their primary water content was also high but that the water had opportunity to escape along fewer though relatively open fractures that reached the surface. Along such fractures some of the water may have escaped to supply the volcanic vents, there to produce the effects that have so impressed the volcanologists.

The widespread serpentinization and chloritization associated with the subsiliceous intrusives shows that in these rocks, also, magmatic water has been very abundant.[28] Whether the water was indigenous to the magma of the pyroxenite parent of the serpentines or was derived by later differentiation at depth, it was almost surely magmatic in ultimate source.

All these evidences, volcanic and plutonic, seem clearly to show that not only was the primary water content of granites and gabbros greater than 0.84 per cent and 1.45 per cent respectively, but that it was very much greater. An estimate of six or even eight per cent for primary water in granite magma at depth seems much more in keeping with geologic evidence than an estimate of one or two per cent. Gabbro magmas are probably less hydrous, but Grout[29] has accepted, on geologic grounds, an estimate of four per cent for the primary water content of the Pigeon Point diabase sill.

Another line of attack on the problem may be mentioned, though it is not worth much emphasis at this stage of the knowledge of earth physics. This is a comparison of the mass of the hydrosphere with the mass of the differentiated rock from which, according to many cosmogonists, it must have been derived.

If we assume that the basaltic oceanic floors represent the undifferentiated substratum (the parental magma, from which

[28] Benson, W. N.: The origin of serpentine: This Journal, Vol. 46, pp. 693-731, 1918.

[29] Grout, F. F.: Anorthosite and granite as differentiates of a diabase sill on Pigeon Point, Minn.: Geol. Soc. America Bull., Vol. 39, p. 568, 1928.

the continental granites have all been derived) then the water content of such basalt should give a rough measure of the primary water content of the parental magma. Probably a little loss would be conceded, even for these basalts, but their water content should clearly be a minimum measure. According to Clarke and Washington's averages, the average rock of the South Atlantic islands carries 1.47 per cent of water, that of Polynesia 1.16 per cent.

However, if the suboceanic basalts are assumed to be undifferentiated, it must be assumed in accordance with most theories of cosmogony and petrogenesis, that the continental blocks furnish the only sites of notable differentiation, hence that the water of the earth was derived by differentiation of the magma column beneath the continents alone. It is of interest to make a rough calculation as to the quantity of magma that must have been involved in order to liberate the water of the hydrosphere.

According to Clarke and Washington the hydrosphere makes up about seven per cent of the mass of the ten mile crust of the earth. If it be assumed that sial covers 0.3 of the earth's surface and a further 0.2 be allowed for sial immersed in the oceans (Daly), then this water would be derived from the differentiation of the primitive magma underlying half the earth's surface. Now we know that the femic fraction of this differentiation does not furnish anhydrous rocks. The average dunite of Daly has 2.88 per cent of water, the average harzburgite 5.02 per cent, and the average amphibole peridotite 4.56 per cent, so that the water of the assumed primary magma was by no means all thrown with the salic fraction during differentiation and hence was still farther from being all concentrated into escaping solutions. Even the eclogites carry as much as 0.25 per cent of water despite the probability that most of them have been subject to metamorphic differentiation through long periods, during which much of their water content could have been "sweated" out.

If seven per cent of the ten mile crust is water, and if it is all derived from differentiation of the magma underlying half the earth's surface, we have a crude minimum measure of the primary water content of this magma, according to the depth of the magma column that is assumed to have been involved. According to Daly's assumptions of earth stratification the crystalline sima beneath the continents is reached at a depth of about 40 kilometers or 24 miles. Were all the water derived from this thickness of magma the excess water liberated during the differentiation was fully 5.8 per cent, and, allowing for 0.84 to 1.80 per cent of water in the average crystalline granite and plateau basalt respectively (Daly), the original water content of this magma column was roughly 6.6 to 7.6 per cent.

This assumption is, of course, arbitrary. Doubtless some of the water of the hydrosphere was given off in the crystallization of the suboceanic basalts. In so far as this is true, however, it is obvious that the primary content of the basalt must have been higher than that determined on the crystallized oceanites and basalts of the oceanic islands. We are not compelled to accept the high figure just mentioned, but in so far as we decrease it we are compelled to increase the assumed primary water content of the basaltic substratum.

This paper presents nothing novel in igneous geology. At present it is fruitless to try to get any precise figures for water content of magma deep in the crust. But it is submitted that the geologic evidence requires estimates far higher than one or two per cent of water for the primary magmas and that figures of fully four per cent for basalts and perhaps as much as eight per cent for deep granites are more reasonable than the smaller figures that have been recently advocated.

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