THE WATER CONTENT OF PRIMITIVE GRANITIC MAGMA*

EARL INGERSON, *U. S. Geological Survey, Washington, D. C.*

ABSTRACT

Previous estimates of water content of magmas are summarized. Assuming that essentially the amount of water now on the Earth's surface was in a primitive atmosphere and that this atmosphere was in equilibrium with a molten outer layer of the Earth as it began to crystallize, the amount of water in this "primitive magma" can be calculated. It comes out about 3%.

INTRODUCTION

An estimate of the amount of water in magma depends directly upon certain assumptions, such as the mechanism of derivation of the magma, physical conditions in the surrounding medium, relation of the magma chamber to the surface, and conditions at the surface. It is also likely to depend indirectly upon an individual's idea of how much water must have come from a given rock mass to produce certain observed effects; in other words, on his idea of how much water the magma *should* have contained. For these reasons estimates of water in magma have ranged from almost nil to many weight per cent.

PREVIOUS ESTIMATES OF WATER IN MAGMA

Green (1887) and later Brun (1911) maintained that magma, at least where it comes to the surface in volcanoes, is essentially anhydrous. Most other workers have concluded that water is usually, if not always, the chief agent in volcanic activity and that it is also important in the activity of intrusive magmas that do not reach the surface.

In 1847 Scheerer (p. 491) estimated that the water content of granitic magmas was between 1 and 50% and suggested that the true value was probably nearer the minimum figure—possibly 5, 10, or 20%.

Lindgren (1905) concluded from the fact that pitchstones contain up to 8% of water that the magmas from which they were derived probably contained a like amount but that "all magmas may, of course, not have contained this amount." Allen (1922) used the same argument in discussing a pitchstone containing 10.5% of water, . . . "Since hygroscopic water in rocks of this nature is insignificant, and since the rock showed no sign of alteration, we may infer that most of this water was contained in the original magma." Hawkes and Harwood (1932), however, in discussing the glassy border phase of a dike that contains 5.88% of water, arrived at a quite different conclusion. They had evidence that the dike could not have been more than 0.5 km below the surface at the time of

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intrusion and pointed out that, from Goranson's data, (1931), the magma could not have contained more than 1 to 2% of water at the pressure prevailing at that depth and at a temperature of 900° to 700° C. They concluded, therefore, that "the bulk of the water now in the glass was not held in the magma on emplacement, but has been added later." They find it "reasonable to suppose that the water was added from the interior of the dike, from which it was expelled on crystallization."

Vogt (1922) arrived at a figure for water in the "initial parent magmas" by assuming that the water in the oceans plus that in the crust (2.02%) was originally in solution in a shell 30 miles thick. On these assumptions the original water content would have been 4.06%. Vogt believed, however, that some water would have escaped before crystallization began and that the water content of the derived "partial" magmas was always less than 4% when crystallization began.

Tyrrell (1926, p. 47) estimated that the basaltic magma of the Hawaiian Islands contains about 4% of water.

Grout (1928) suggested that 4% might be a valid figure for the water content of the magma from which the diabase sill on Pigeon Point, Minnesota, was formed. There is no direct evidence on which to base such an estimate, but the olivine diabase contains well over 1% of water and "many observations show conclusively that magmas contain more water than the igneous rocks formed by their crystallization" (p. 568). Grout cited the 4% estimate of Tyrrell and concluded that the estimate of 4% of water in the primary magma of the sill was therefore not unreasonable.

In this same paper (p. 568) Grout says, "Acid rock magmas, such as form pitchstone and pegmatitic granite, may contain 10 to 20% of water." He does not support the statement with examples, literature references, or a theoretical discussion.

Bowen believes (1928, p. 301) that the average basalt magma may not contain more than 0.5% of total volatiles originally, which would, of course, mean a water content of less than 0.5%. He suggested (p. 302) that with crystallization of anhydrous phases and consequent accumulation of water, the water content may rise to a maximum of 4 or 5%. For magma with the composition of granite the estimate is less than 1% of volatiles (p. 296). He indicated (p. 297) that exceptional magmas (such as gave rise to pitchstones) may have contained water up to the order of 10%. He believes that such cases are decidedly abnormal and that the normal granitic magma contains much less water, probably less than 1%.

Later (1933, p. 117) Bowen used a hypothetical example in which he assumed 0.5% original water content of a granitic magma. He thinks that after the water content has reached 2 or 3%, hydrous phases may form by reaction so that the water content never increases beyond this value, and the final product would be a granite with 0.5% of water.

Goranson (1931) determined experimentally the amount of water that would dissolve in molten Stone Mountain granite under various pressures at 900° C., which is a reasonable figure for the beginning of crystallization in a granite. The amount of water that dissolved in the melt approached 10% as the pressure was increased, being 9.35% at 4000 bars. The curve flattened rapidly above 3000 bars. In applying these results to magmas he assumed that crystallization took place from the center of the Earth outward, progressively expelling the water until most of it was concentrated in a molten granitic layer some 15 km thick adjacent to the surface. *If* there was enough water present to saturate this layer, the amount of water at a given spot depended upon the composition of the (anhydrous) melt, the temperature, and the pressure.

From this postulated setup and his experimental work, Goranson calculated the water content at various depths, assuming granitic composition and a temperature for each depth considered. He concluded that if these conditions represent rather closely those obtaining in nature, rhyolite glasses could not very well have more than 10% of water and that glasses with 8 to 10% of water should be extremely rare. He pointed out that this conclusion appeared to be supported by analyses of fresh obsidians.

Phemister (1934) estimated that plutonic basaltic magmas contain 4 to 5% of water and that similar magmas that are less deep-seated contain less water in solution. This figure is obtained indirectly. Phemister made a detailed study of crystallization of a hydrous melt in the system K_2SiO_3-SiO_2-H_2O (from Morey's diagrams) to evaluate the external factors affecting crystallization of an "ideal" basalt magma and arrived at the above-mentioned estimate for the amount of water in such a magma.

Gilluly (1937) estimated that basaltic magmas may contain about 4% of water; granitic, about 8%. These figures are based on evaluation of geologic data. Gilluly believes that water contents of this order of magnitude are necessary to explain observed activity of volcanoes, and the amounts of migmatization and granitization that have accompanied many granitic intrusions.

Hess (1938) suggested that some ultrabasic magmas may contain as much as 5 to 15% of water in solution. This is based on his idea that serpentinization takes place during the later part of the crystallization of the magma. A completely serpentinized rock contains about 13% of water, which is the same order of magnitude as Hess' maximum figure. If Hess' ideas of the origin of such rocks is correct, then magmas with such water contents must have existed.

Grout (1941) took 10% as the part of a magma that may have been volatile. For simplicity he assumed that this is water carrying 10% of mineral matter in solution. Apparently the 10% water was taken because it accords roughly with the amount (8%) estimated earlier by Gilluly (1937). Assuming 10% of mineral matter in solution gives 1% as the amount of the nonvolatile portion of a granitic intrusion that might be mobile in this manner, Grout pointed out that this is the proportion of pegmatite in granite estimated by Vogt (1931).

Daly (1944) extrapolated Goranson's curves to 23,000 atm (minimum pressure on the basaltic substratum) and decided that at this pressure granitic magma could contain 12% of water. He believes that under the same conditions basaltic magma might contain 5 to 10% of water. In the absence of experimental work on materials of basaltic compositions, Daly assumed that basaltic magma would dissolve about half as much as granite, i.e., magma in the basaltic substratum would carry 6% of dissolved water.

Daly pointed out that as the magma ascends into the Earth's crust water is likely to escape. He concluded, apparently in part from his estimate of original water content and in part on the basis of analyses of fresh basalt flows, that basaltic magma may reach the Earth's surface with as much as 2 or 3% of water and may retain this amount even after solidifying.

Graton (1945) cited earlier estimates of water content of magmas by Bowen, Gilluly, and Goranson, and concluded that the solubility *limits* in nature probably range from 5 to 11% of volatile content for the various common magmas, but that actual water contents of lavas as brought to the surface in volcanoes are consideraly less. He suggested that when the water content of lava is not more than 2 or 3% quiet extrusions take place, but that when the water content exceeds a critical value of about 3% explosive ejection results. Goranson's results undoubtedly had some influence on Graton's choice of 11% as the upper limit, but another consideration also entered. He calculated that the expansion and escape of still larger proportions of volatile constituents would produce such a cooling effect that the magma would be chilled almost immediately and bring activity to an end. Since this effect is not observed in volcanoes, the magma cannot have contained much more than about 10% of water.

BASES OF PREVIOUS ESTIMATES

All of these estimates of the water content of magma can be divided into a few groups according to the basis on which the estimates were made:

(1) On the basis of the water content of igneous rocks.

(2) On the basis of the observed effects of emanations from igneous rocks.
(3) Experimental determination of solubility of water in silicate melts.
(4) Assuming that all water now at the surface has been derived from crystallizing magma. A thickness for the shell from which the water was derived must be assumed, of course, in order to obtain an estimate for original water content.
(5) Combinations of (1) to (4).

ASSUMPTIONS FOR PRESENT CALCULATION

It is interesting to start with an entirely different set of assumptions, as nearly as possible independent of the considerations mentioned above, and to see how the results compare with previous estimates. Let us assume:

(1) That, at an early period in the Earth's history the outer layer, at least, was molten.
(2) That essentially the same amount of water was present on the Earth's surface then as we find today in the hydrosphere, the biosphere, the atmosphere, and the sedimentary rocks.
(3) That, at the time crystallization began, equilibrium had been established between this primitive atmosphere and the molten crust—the original magma from which at least most of the igneous rocks found at the surface today have been derived either directly or indirectly.

The first assumption has purposely been simplified. This simplification is probably justified. There is ample geophysical evidence of a compositional-density zoning in the Earth, so if convection has been operative the currents probably have been confined to individual layers and would not have extended from the surface into subcrustal layers.

There is no way to make an accurate check on the second assumption, but the evidence is that the ocean basins have had about their present area and volume throughout geologic history and that they have been filled to about the same level with water during all that time. The earliest known pre-Cambrian sedimentary rocks are widely spread over the continental masses. If the amount of water on the Earth's surface had been increasing or decreasing steadily and significantly throughout geologic time then there should have been a general and progressive increase or decrease in the area covered by progressively younger sedimentary rocks. Because of coverage and erosion of large amounts of sedimentary rocks, it is not possible to estimate areas covered by rocks of various ages very accurately, but the paleogeographic maps thus far compiled fail to show any such consistent trend in either direction.

As to the third assumption, under the postulated conditions equilibrium would obtain at the surface of contact between the molten crust and the primitive aqueous atmosphere. The (assumed) thickness of the molten layer saturated with water under these conditions in no wise affects the calculations that follow, because the water on the surface is that which was left *after* equilibrium was established. Increasing pressure with increasing depth has no meaning in this situation, as it has for Goranson's and for Daly's calculations, because the water comes from the outside and it is not possible to get more water in the lower part of the layer than the equilibrium amount at the surface. Even if the vapor pressure of the water could act directly on the lower parts (which it could not through a viscous glassy layer) the pressure of the magma would have no effect. The difference would be due to the increased height of the water-vapor column and would not be significant.

CALCULATION OF WATER CONTENT

Granted the assumptions, the calculations are straightforward and give a value that is subject to relatively slight uncertainty.

At the temperature where crystallization would begin, all the water on the surface would be in a gaseous envelope. The pressure per unit area of the superincumbent water vapor would be the total weight of the water in the gaseous envelope divided by the area of the interface, i.e., the Earth's surface. Rubey (unpublished manuscript) estimates that all the water in the hydrosphere, atmosphere, biosphere, and sedimentary rocks amounts to 1.67×10^{24} g. The Earth's surface is approximately 5.1×10^{18} cm^2, so the pressure of the water vapor per unit area would have been

$$\frac{1.67\times10^{24}}{5.1\times10^{18}}=3.3\times10^{5}\ \mathrm{g/cm^2}=330\ \mathrm{kg/cm^2}.$$

Anhydrous granite melts at about 1200° C. Under 1000 bars pressure of water vapor it melts at about 700° C (Goranson, 1931, p. 499). If we use these two figures and draw a curve shaped like the one for melting-point lowering of sodium disilicate with increasing water-vapor pressure (Fig. 1), it will be seen that under a pressure of 330 kg/cm^2 granite would begin to crystallize in the neighborhood of 900° C. According to Goranson's experimental results (1931, Fig. 3) a granite melt under these conditions would contain very close to 3% of water.

O. F. Tuttle, of the Geophysical Laboratory, very kindly made two runs of Stone Mountain granite with water at 725° C and 2000 kg/cm^2. In both runs the product was entirely glassy, containing 6.1 and 6.7% H_2O respectively. The technique was entirely different from Goranson's, but the solubility indicated is of the same order of magnitude. Tuttle's lower results may be explained by the short duration of the runs—2 hours—because water penetrates viscous high-silica melts very slowly. Charles E. Kinser, of the U. S. Geological Survey, analyzed the samples for water.

Under the above assumptions, therefor, the primitive granitic magma underlying the continents would have contained approximately 3% of water. No experimental results are yet available for solubility of water in basaltic or peridotitic melts. If and when such experiments are performed the water content of primitive magmas of these compositions can be derived from the above assumptions by analogous calculations.

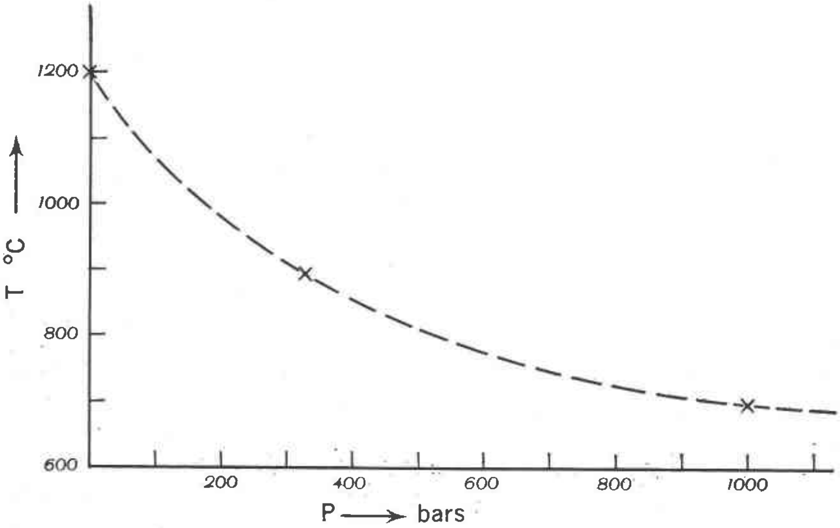

FIG. 1. Curve showing the decrease in melting point of granite with increasing pressure of water vapor. The points at atmospheric pressure and at 1000 bars were determined experimentally by Goranson (1931). The shape of the curve is patterned after that of the system $Na_2Si_2O_5$-H_2O. At 300 kg/cm^2 the melting point of granite would be very close to 900° C.

After crystallization had proceeded to a point where a solid shell existed and at least a considerable part of the water from the primitive atmosphere had condensed the problem would be quite different. It is probable that the *average* magma would still contain approximately the original 3% of water, but locally derived secondary magmas might vary considerably in either direction.

For example, a body of magma near the surface at low pressure might lose quite a lot of its water and so have less than 3%. Or there might be local intrusions of relatively anhydrous magma squeezed up from the underlying layer that was never in equilibrium with the aqueous atmosphere.

On the other hand, crystallization of anhydrous phases might concentrate water in a rest magma that could be filter-pressed away and so produce a secondary magma with much more than 3% of water. Fusion of depressed hydrous sediments might produce a similar result.

The question of the water content of secondary magmas is in each case a separate problem and all available data must be sought and used in its solution.

SUMMARY AND CONCLUSION

TABULAR SUMMARY OF ESTIMATES OF WATER IN MAGMA

Date	Author	Type of magma	% Water	Method of estimating; assumptions; remarks
1847	Scheerer	Granitic	1 to 50 5, 10, or 20 probable	
1887	Green		0	
1905	Lindgren	High silica	Up to 8	Water content of pitchstones.
1911	Brun		0	
1922	Allen	High silica	Up to 10	Water content of pitchstones.
1922	Vogt	Initial parent	4	Water in and on crust originally uniformly distributed in 50-km shell.
1926	Tyrrell	Basaltic	4	
1928	Grout	"Diabasic"	4	Present water content of diabase sill+Tyrrell's estimate.
1928	Grout	"Acid" and pegmatic	10 to 20	
1928	Bowen	Basaltic	<0.5	Original.
			4 to 5	Maximum after crystallization of anhydrous minerals.
1928	Bowen	Granitic	<1.0	Common case; most obsidians <1.0% water.
			8±	Exceptional; some pitchstones show such quantities of water.
1931	Goranson	Granitic	<10	Exp. det. of solubility of water in granite melts; calculation for estimated temperature and pressure at various depths in Earth.
1933	Bowen	Granitic	0.5 orig.	
			2 to3 max.	Hypothetical example.

TABULAR SUMMARY OF ESTIMATES OF WATER IN MAGMA (*continued*)

Date	Author	Type of magma	% Water	Method of estimating; assumptions; remarks
1934	Phemister	Basaltic	4 to 5	Analogy with system K_2SiO_3-SiO_2-H_2O.
1937	Gilluly	Basalt	4	Geologic data, volcanoes, etc.
1937	Gilluly	Granitic	8	Geologic data, granitization, etc.
1938	Hess	Ultrabasic	Up to 15	Field evidence on serpentinization and related phenomena.
1941	Grout	Granitic	Up to 10	Accords with Gilluly; can explain 1% pegmatite estimated by Vogt.
1944	Daly	Granitic	12	Extrapolates Goranson's results to 23,000 atm (base of crust).
1944	Daly	Basaltic	6	Assumes that one-half as much water will dissolve in basaltic melt as in granitic.
1945	Graton	"Common"	5 to 11 volatiles	Goranson's results plus consideration of cooling effects of escape of larger quantities of volatiles.
1950	Ingerson	Granitic	3	Approx. limit for nonexplosive volcanic activity.
			3	Assumes equilibrium between primitive atmosphere containing all water at present on Earth's surface and a molten outer layer.

It is concluded that, if the assumptions made are valid, the primitive (granitic) magma of the Earth's outer layer contained approximately 3% of water. Later magmas derived directly or indirectly from the primitive one or produced in other ways may have contained either more or less water. It is probable, however, that any marked deviation from the original 3% is unusual and that most magmas contained approximately this amount of water when they began to crystallize.

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