The frequency-distribution of igneous rocks.

Part II. The laws of distribution in relation to petrogenic theories.

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1. *The Law of Distribution.*

IN Part I[1] of this paper the actual frequency-distribution of igneous rocks as revealed by the latest edition of Washington's collection of analyses was examined, and compared with that of earlier records. An attempt will now be made to determine the law of this distribution —a necessary preliminary to any petrogenic application of the results. The silica frequency will be considered since this has been found to give a curve more characteristic of igneous rocks than does any other oxide. Now Dr. Harker[2] pointed out that the silica distribution of records published in 1903 did not obey any simple law such as that of the probability curve, and the same conclusion applies to the collection of 1917. However, when the empirical method of Karl Pearson[3] was

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[1] W. A. Richardson & G. Sneesby, Min. Mag., 1922, vol. 19, pp. 303–313.
[2] A. Harker, Nat. Hist. of Igneous Rocks, London, 1909, p. 148.
[3] Karl Pearson, Chances of death and other studies in evolution, London and New York, 1897, vol. 1, p. 26.

applied to analyse the curve into component curves of error, fairly simple conclusions resulted.

This attempt at analysis was suggested largely by the close resemblance that the extreme ends of the distribution showed to portions of normal curves of error. In fact the frequency curve appeared divisible into three parts :—(1) A semi-normal curve at the ultrabasic end. (2) A typical U-type distribution between the modes. (3) Another semi-normal curve at the ultra-acid end.

It was discovered that normal curves could be fitted to these extreme portions with exactness. In fig. 1A the chosen equations are plotted and written against the curves. The chain-dotted portion is the result of adding ordinates, and the small circles give the positions of the actual frequencies. It is clear that the distributions mutually modify one another but little, and only over a very narrow range.

Two normal curves of error, situated at the modes of the actual distribution, therefore, reproduce the frequencies below 52 and above 72. Centrally, however, while the combined curve reflects the general character of the actual distribution, the fit is less exact than at the outer edges. Further, the influence of the basic curve at the acid mode is almost negligible; and vice versa.

In order to investigate the deviations in the central region, differences between the ordinates of the combined curve and the observations were taken out. These are plotted in the lower diagram (fig. 1B) which may be called the *curve of residuals.* Its vertical scale is half that of the main diagram, but for ease of comparison it is plotted beneath to the same horizontal scale.

If the fit were perfect the curve of residuals would be a straight line coinciding with the axis of X. In the outer regions, indeed, there are only small oscillations on either side of the zero-line showing that the fit here is a fair one. The deviations from R to S, i. e. between the modes, are more formidable. There is a large negative part close to R, followed by a rather irregular group of large positive residuals, and the meaning of this arrangement becomes a matter of interest. Three possible causes of such a disturbance suggest themselves :—

1. There might be a subordinate mode near 64, with a suite of rocks distributed normally around it. This leaves the negative parts somewhat deepened, and there are other objections to this interpretation which will appear in the sequel.

2. There may be certain special processes affecting this region, which do not involve a normal distribution, and will be considered later.

3. The oscillations in the part *RS*, though of greater amplitude, are essentially of the same nature as those at the ends, and may be due to the same cause, namely, irregularities in the sampling which may ultimately be reduced when the collections become representative. Since Daly's investigation points to low frequencies in this region, it seems

Distribution Law

$$y = 190e^{-\frac{(x-52\cdot5)^2}{72}}$$

$$y = 160e^{-\frac{(x-72\cdot5)^2}{20\cdot5}}$$

(A)
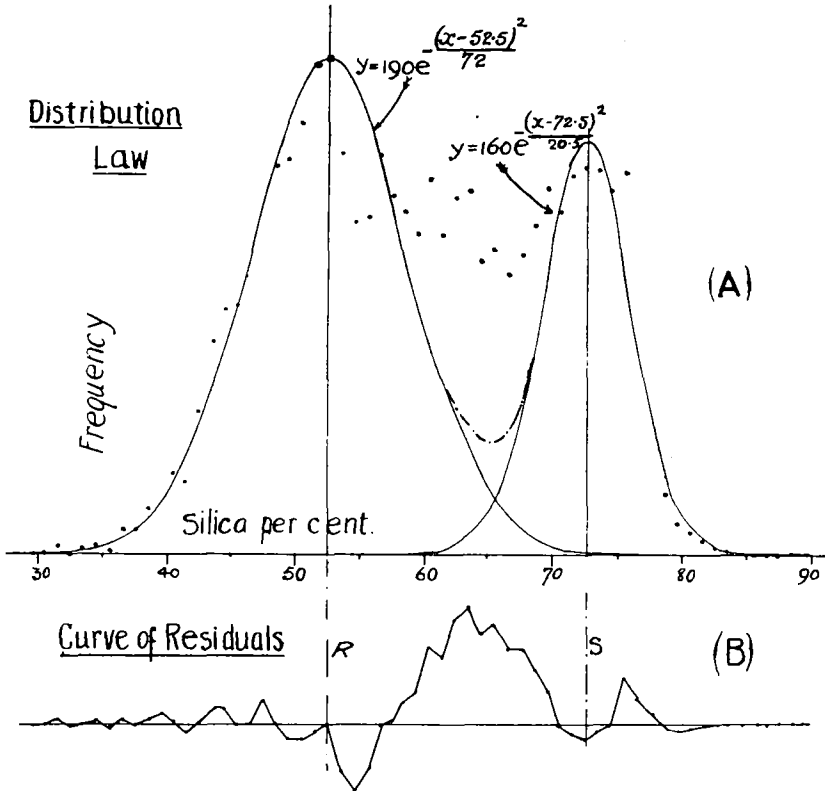
Frequency

Silica per cent.

Curve of Residuals (B)

FIG. 1. Analysis of the frequency-distribution of silica in igneous rocks.

likely that this is the true explanation of much of the divergence. On the whole, the matter must be regarded as *sub judice*, and definite conclusions will not be possible until at least one further edition of the collection is available.

Meanwhile, the law of distribution of igneous rocks, deduced from consideration of silica, may be considered as expressed by the sum of two probability equations. It may be stated in the following form,

namely, that igneous rocks visible at the earth's surface are grouped about two poles—an acid and a basic—such that their distribution about these conforms more or less closely to two combined curves of error.   In other words, *there are two main rock types, one of a basaltic and the other of a granitic character, and all others may be regarded as chance variations about them—meaning by the term 'chance', of course, merely that small departures from type are more probable than large departures.*

Space does not allow of a detailed analysis of the frequencies of the other oxides.   They are less characteristic, having smaller dispersions, but it may be stated that they reveal no features antagonistic to the law just stated.

2. *Causes of Rock Variation.*

I suppose it may be taken as axiomatic that any general theory of petrogenesis must be competent to account for the frequency-distribution of igneous rocks when this is definitely known.   It appears, however, that processes capable of giving rise to different rock types have not been examined as to the frequency-distribution likely to result from them.   Hence it will be necessary to examine petrogenic factors from this standpoint.

Continuous Composition Gradients.—Continuous variation in temperature, with a corresponding composition gradient, is not now regarded as a serious factor in petrogenesis.   But it has been suggested that a fluid stratification due to gravity may be operative, especially at an early stage in planetary history.   Let us consider this action applied to a magmatic body of constant cross-section.   The composition will be some function of the depth.   Now the body can be divided into a number of equally spaced, horizontal strips each of such a thickness that the composition of the strip may be assumed uniform.   The magma will consolidate as a large series of rocks, with compositions varying according to the law of depth, and with equal volumes.   In other words, all types will have the same frequency, and the resulting distribution diagram will be a rectangle as in fig. 2—the terminal ordinates being situated at points representing the composition of the top and bottom layer respectively.   It should be noted that the actual form of the composition law, providing variation be continuous, has no effect on the frequencies, but only on the spacing of the ordinates.

The Principle of Limited Miscibility.—If the power of a magma to split spontaneously into two partial magmas were at all comparable to
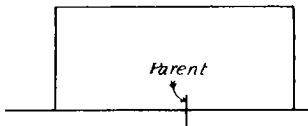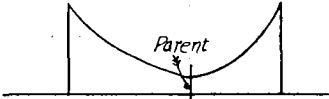
Fig. 2. Composition Gradients.
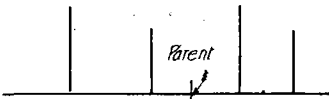
Fig. 3. Limited Miscibility
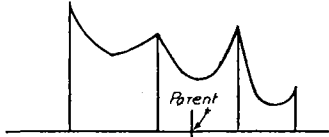
Fig. 4. Limited Miscibility.
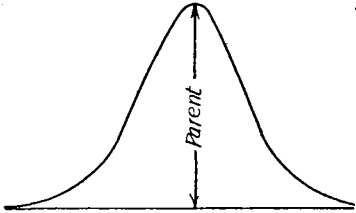
Fig. 5. Limited Miscibility.
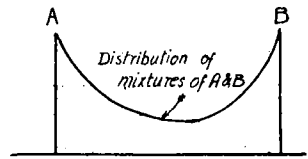
Fig. 6. Crystallisation-Differentiation
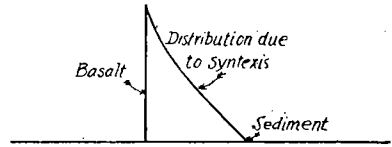
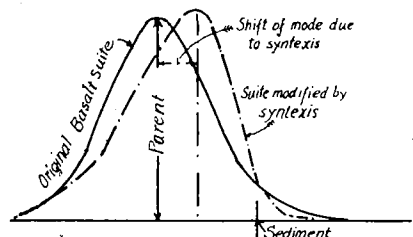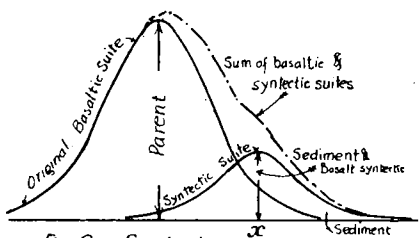Fig. 10. Magmatic Mixing.

Fig. 7. Syntexis

Fig. 8. Syntexis.

Fig. 9. Syntexis.

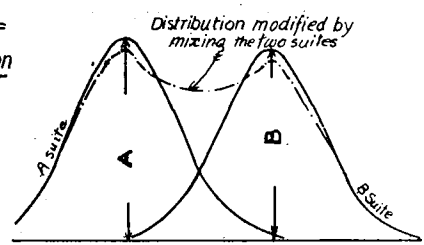NOTE. Abscissae represent oxide percentage
Ordinates represent frequency

Fig. 11. Magmatic Mixing.

FIGS. 2-11. Types of frequency-distribution.

that of a mixture of chloroform and water, as soon as the temperature was lowered to the point of separation the parent magma would disappear completely and two partial magmas would take its place. The frequency diagram would simply consist of two vertical lines situated at the compositions of the partial magmas.

Now if some such property of the magma as viscosity should hinder the separation, so that in some cases the time available (between the temperatures of separation and crystallization) were too short to allow of complete segregation, then some small portions of the parent magma might be left, and there would be also intermediate products. The distribution curve would still show large ordinates at the end-members with a curve tailing down to that of the parent type (fig. 3).

There remains the possibility that instead of two partial magmas only being formed, a considerable number of immiscible fractions may develop from the parent magma. If the separation in this case were complete, the frequency-distribution diagram would again consist of a number of isolated ordinates of different heights, and the parent magma would disappear in the process (fig. 4). If complete separation were not possible, intermediate types would be present, but the diagram would still present abrupt ends, and perhaps approximate to a crude rectangular shape (fig. 5), for in the limit this process must result in frequencies closely resembling the stratification of a liquid under gravity; because, although the variation theoretically would be discontinuous, the formation of numerous fractions (which could only be separated by gravity as Bowen[1] points out) would in practice form a nearly continuous series.

Fractional Crystallization.—Magmatic differentiation by crystallization depends on some mechanism for segregating the crystalline phase. Diffusion to maintain supersaturation is resorted to by Harker to explain differentiation in place, but since the matter is still in controversy, and applies only to individual rock bodies, it may be passed over here. This may be done the more readily because all advocates of fractional crystallization admit the importance of gravity control, aided by earth movement, in the production of igneous rocks on a large scale;[2] and also because localization of crystallization as advocated by Harker would probably produce frequency effects not very different from gravity control.

[1] N. L. Bowen, Later stages of the evolution of igneous rocks, Journ. Geol., 1915, vol. 23, supplement p. 8.
[2] A. Harker, Congrès géol. internat.   Compte-rendu for 1913, 1914, p. 208.

The determination of the probable frequency-distribution of the derivatives of a magma produced by fractional crystallization is considerably aided by the work of Bowen, who has studied the subject in a long series of recent papers, and has subjected the matter to a large number of ingenious experiments. In view of this work we may conveniently think of the differentiation of an olivine-basaltic magma.[1]

Now it should in the first place be noted that there is no formation of sharply-defined end-members, as in the case of limited miscibility, but only of 'a partially different assemblage of minerals', which differs in different cases. Again, 'those opposed to the process seem to expect too much of it, especially in the way of a sorting of the individual minerals'.[2] In fact, there are many causes operating to prevent a separation of the minerals, some of which have been pointed out by Bowen himself. Convection currents, even though small; streaming during and after injection; and rapid cooling would all hinder separation of crystalline phases especially in the case of extrusions. Overlapping of crystallization periods of minerals is a factor of considerable importance. Thus, as Bowen points out, the crystallization of ore-minerals alone would be brief, especially in the smaller bodies, and there would be a long period during which crystals tend to 'sink through the liquid as a swarm . . . the sinking being determined by the mean density of the swarm'. Further, as soon as crystallization has well begun, the sinking of crystals must take place not through a clear liquid, but one filled with the tiny crystals of minerals just beginning to separate. The ordinary viscosity of the magma in conjunction with the frictional resistance produced by scattered crystals must operate against separation especially when the shape of crystals is taken into account. For it is not merely the *size* of crystals, as Bowen assumes, but also the amount of surface presented to the medium that determines the rate of sinking. Thus rounded grains of olivine will settle with ease compared with biotite flakes, although both have nearly the same density. Again, Vogt[3] has drawn attention to the fact that the minerals of later crystallization tend to attach themselves to those of earlier stages, and

[1] N. L. Bowen, Differentiation in silicate liquids, Amer. Journ. Sci., 1915, ser. 4, vol. 39, p. 186.

[2] N. L. Bowen, Later stages in the evolution of igneous rocks, Journ. Geol., 1915, vol. 23, supplement p. 15.

[3] J. H. L. Vogt, On labradorite-norite, Quart. Journ. Geol. Soc., 1909, vol. 55, pp. 81–103.

in this way spread-out, 'spongy' aggregates result that will settle only with great difficulty. Finally, monomineralic rocks, the result of extreme sorting, are relatively rare, and, as Bowen has shown, require somewhat special conditions for their formation.[1]

Now the parent rocks—olivine-basalts, dolerites, and gabbros—are abundant in nature not only as separate bodies, but in complexes. Thus, for example, we are told that two-thirds of the Duluth gabbro (three miles thick) is of olivine-gabbro.[2] Moreover, given the same assemblage of minerals, the chemical composition will vary on account of the phenomena of mix-crystals and solid solution.

Taking all these points into consideration it may be concluded that the frequency of those rocks *near* the parent type will be greater than those more remote; and the more extreme types will be rare. The type of distribution, therefore, will be such that small departures from type are more probable than large, and that in the long run the distribution about the mean will be normal (fig. 6). *It may then be concluded that differentiation by crystallization under gravitational control results in a frequency-distribution that conforms to a normal curve of error.*

Syntexis.—Assimilation of sediments by igneous rocks has been advocated strongly as a cause of rock variation especially by Daly and Cole. Let us consider the effect of the assimilation by a basalt of a sediment more acid than itself. There are at least three important cases.

1. When simple mixing alone occurs no rock more basic than the basalt can be produced and none more acid than the sediment. Moreover, no igneous rock can be produced of the same acidity as the sediment. The frequency diagram of the igneous suite produced will be terminated at the compositions of the two participants; it will be extremely asymmetric (J-type) with a mode at the principal parent basalt and have a zero ordinate at the position of the sediment (fig. 7).

2. Let there be a suite of basalt derivatives, distributed normally about the parent, and let the sediment be free to mix equally with all members of the basalt suite. Now obviously all rocks more basic than the sediment will have their silica content increased; and all rocks more acid will have their silica content decreased, and therefore, the

[1] N. L. Bowen, The problem of the anorthosites, Journ. Geol., 1917, vol. 25, pp. 209-243.

[2] F. F. Grout, A type of igneous differentiation, Journ. Geol., 1918, vol. 26, p. 637.

main result of sedimentary contamination of the suite will be to *reduce the dispersion*. The mode will also be shifted towards the sediment, and the distribution become asymetric to an extent depending on the frequency of assimilation. These changes in the distribution are shown in the two curves of fig. 8.

3. Let now the syntectics produced be themselves capable of differentiation by fractional crystallization. Let us consider the effect of the formation of a syntectic of composition x, fig. 9. Let the frequency of this syntectic be one third that of the primary basalt, and let the dispersion be the same. The resulting frequency-distribution will, therefore, be the sum of the two curves of error in fig. 9, and the final result of this combination will be: (a) The mode displaced towards the syntectic; (b) Asymmetry—the curve leaning towards the syntectic; (c) An increase in the frequencies of those rocks near the syntectic; (d) A small increase in the dispersion near the syntectic suite, and, in the case figured, on the acid side of the basalt.

Magmatic Mixing.—Let us suppose that two magmas may mix in any proportions; then it is evident that the composition of all derivatives must fall between those of the two primaries. It is also obvious that the frequencies of rocks so produced will depend upon the extent to which this action takes place in nature. If we suppose that small contaminations of the primaries are more likely than large, then the frequency curve will drop away from the frequencies of the primaries to a probable minimum situated somewhere near the composition of the average rock, as in fig. 10. The distribution characteristic of this action is typically U-shaped.

Again, consider the case where there are two main poles, each possessing a suite of rocks derived from them and normally distributed; and where all the derived magmas are free to mix. This represents a somewhat extreme case if we regard fractional crystallization as the main cause of differentiation.[1] However, the general effects of such free mixing on the frequency distribution of the series will be:

(a) to reduce the total dispersion; and (b) to fill partially the valley between the two primaries (fig. 11).

Summary.—We may now briefly summarize the effects upon frequency-distribution due to processes that may be concerned with rock variation. Composition gradients give rectangular types of distribution. Immiscibility in the liquid state, if complete, would give isolated ordinates, and,

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[1] N. L. Bowen, Crystallization-differentiation, Journ. Geol., 1919, vol. 27, p. 405 [Min. Abstr., vol. 1, p. 320].

if but partial, a diagram terminated abruptly, and in general with maximum frequencies at the ends. Differentiation by fractional crystallization ('crystallization-differentiation') seems capable of giving a normal distribution, i.e. one such that small variations from a type are more frequent than large.

The effects of syntexis and magmatic mixing on the whole reduce the dispersion, and the former impresses 'skewness' upon the distribution of a suite of differentiates. The effect of magmatic mixing on the distribution of two primary series would be to produce a partial levelling; or, in other words tend to reduce the modal frequencies whilst increasing those of intermediate types.

Composition gradients tend to make the relative frequencies of all types, including that of the parent, equal. Immiscibility tends to the disappearance of the parent type, whilst crystallization-differentiation preserves it. Syntexis tends to hide or disguise the parent by a shifting of the mode.

3. *Petrogenic Theories.*

In the first section of this paper the frequency-distribution of the different rock types visible at the earth's surface has been found to follow a law such that all types fall into two series normally distributed about two poles—this law resting on the remarkable closeness of fit of two normal curves at the ends of the natural series. In the second section the problem of distribution has been attacked from the other end and distributions likely to be characteristic of different petrogenic processes examined. The data are, therefore, at hand for a discussion of the probable causes of the actual distribution of igneous rocks.

The Theory of Daly.—Daly [1] calls the attention of the petrologist chiefly to the dominance of granitic rocks among plutonics, of basalts among volcanics, and to the mystery of batholithic intrusion. His general theory is largely concerned with the solution of the problems thus raised, and the following are the chief points that concern us here :

1. The primary stratification of the outer portion of the earth is postulated into an outer granitic shell ; a central basaltic shell ; and, below the reach of any eruptive mechanism, a peridotitic shell.

2. Pre-Cambrian granites are a portion of the primary granitic shell, but post-Cambrian batholiths are the result of abyssal injection, the granite being due to assimilation (with subsequent differentiation) of

[1] R. A. Daly, Igneous rocks and their origin, New York and London, 1914.

the overlying sedimentary (or granitic) shell by the abyssal basaltic wedge.

3. Other rocks have arisen partly by differentiation and partly by syntexis—the principle of limited miscibility being regarded as the most important factor in differentiation.

In considering igneous rocks at large it is evident that the ultimate effect of syntexis—so far as sediments are concerned in it—must be the general result of the assimilation of the average sediment. The nature of the raw material for syntexis may, therefore, be gathered from Clarke's [1] estimates of the mean composition of the earth's sedimentary mantle. Sediments total 5 % of the earth's crust and so far as silica is concerned as follows:

Shale 4 % containing 58·1 % silica.
Sandstone 0·75 % containing 78·3 % silica.
Limestone 0·25 % containing 5·2 % silica.

Thus, the average silica content of the sedimentary shell (weighted according to the quantity of constituent rock types) is 58·5 %—an amount not far removed from, but somewhat lower than, the mean for igneous rocks.

Now of these three constituents one only, the limestone, has a lower silica content than Daly's primary basalt, and, moreover, this rock is small in total quantity; and, therefore, by no process of simple assimilation is the distribution of igneous rocks beyond the basic pole likely to be appreciably affected. Further, as already seen, the addition even of sediment at 58 % silica will only affect the region between 52 and 58 %, increasing the frequencies close to 52. In this region there is a defect in the actual frequencies as shown by the curve of residuals (fig. 1). We may therefore conclude that the actual distribution does not show effects likely to be the result of a large-scale operation of syntexis.

But Daly supposes that syntexis and differentiation both operate, and by a combination of the two factors greater effects are possible. The general effect of the superposition of a differentiated syntectic upon a differentiated primary suite has already been considered (p. 9), and the two chief results to be looked for in the natural series are: (1) A partial filling up of the central region, and this indeed has happened, but, on the other hand, may be the result of operation of other causes. (2) A much more characteristic result is the increase of frequencies near

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[1] F. W. Clarke, Data of geochemistry, Bull. U.S. Geol. Surv., 1916, no. 616, p. 32.

the basic pole on the side of the syntectic and a marked leaning over of the basic mode on this side. There is no sign at all of this latter effect, but it has to be remembered that the process recognized by Daly is more complex. He considers, for instance, the assimilation not only of sedimentary material, but also of the granitic primary shell by the basaltic, which by differentiating re-gives granite.
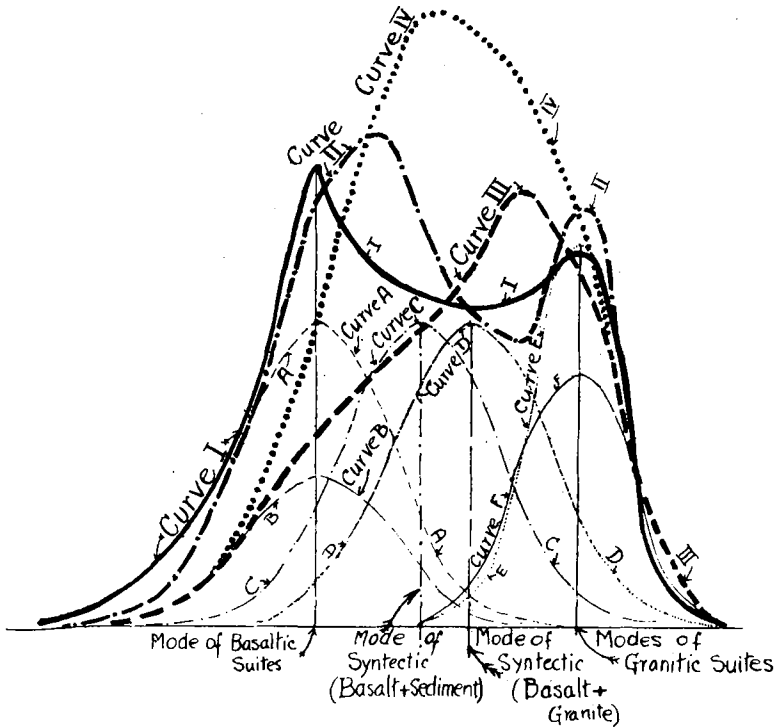
FIG. 12. Curves II, III, and IV show the effects of combining various differentiated syntectics with primary igneous suites. Curve I is the actual frequency-distribution reproduced from fig. 1, Part I, for comparison.

In order to investigate Daly's theory more completely, the curves of fig. 12 have been drawn, assuming that originally two shells of basalt and granite were available in the ratio of 1·3 to 1—the actual ratio does not matter as the general effect of assimilation combined with differentiation on the shape of the curves only is required.

Curve II (fig. 12) is the distribution due to primary granite (curve E);
a syntectic of silica content 58 % (curve C) formed by one-third of the
primary basalt absorbing an equal amount of average sediment ; and the
remaining basalt (curve A). The resulting suites, A, C, and E, are
normal. Curve II is formed by adding the ordinates of the component
curves. The result is asymmetry at the basic end; reduced dispersion ;
and shifting of basic mode towards the centre.

The relative frequencies in the actual distribution and in one thus
modified by syntexis are summarized in tabular form below—the ratio of
post- to pre-Cambrian granites being taken from Daly's tables, and the
scales obtained by assuming 200 as the frequency of basalt for both
curves.

I.   Actual Distribution (Curve I).

Basalt (at mode) silica 52 %	...	...	200
Total granites (at 73 %)	...	...	160
Pre-Cambrian granite (ditto)	...	...	100) (Daly's
Post-Cambrian granite (ditto)	...	...	60 } ratio).[1]

II.   Distribution modified (Curve II).

Basalt at 52 %			200
Granite from primary distribution equivalent to pre-Cambrian			160)
Granite from syntexis equivalent to post-Cambrian			2 } 162 total.

It is, therefore, apparent that even with a liberal allowance for the
amount of syntexis, and for its dispersion, post-Cambrian frequency is at
least thirty times as great as the syntectic granite, and the syntectic
effect on the granite frequency is almost negligible.

Curve IV is the sum of a more complex series :—a syntectic (curve C)
with basalt and sediment as before; a syntectic (curve D) formed by
another third of the basalt with an equivalent amount of granite, giving
a syntectic of acidity 62 ; the remaining basalt (curve B), and the remain-
ing granite (curve F). All are differentiated as before ; the effect of
adding further assimilated series is striking ; there is only one mode in
an intermediate position ; the distribution is asymmetric, and the total
dispersion is *much* reduced as appears on calculating the standard devia-
tion, although not very obvious on the diagram because the scales are not

[1] R. A. Daly, loc. cit., p. 44.

comparable.   The relative frequencies, on the basis that the basalt
remains at 200, are :

Basalt (at 52 %)	...	...	...	200
Total granite (at 73 %)		...	...	270
Syntectic granite (at 73 %)	...		...	90
Intermediate rock at mode (55 %)			..	400

The ratio of the granites is thus altered, and the syntectic is now more
or less adequate to account for Daly's pre-Cambrian ratio, but a frequent
intermediate type about which all rocks are grouped has appeared.

Curve III gives still greater prominence to the amount of acid
material, now the basic mode has disappeared, and the asymmetry is
towards the acid side, but the total amount of granite is much greater
than that of basalt—a distribution again not in accordance with the facts.

Further syntectics could of course be added in this way, but the drift
of the general changes can be gathered from the examples considered.
A syntectic approximating to granite in composition will have little or
no effect on the distribution—it will leave us just where we were so far
as granite frequencies are concerned.   Similarly, a syntectic of basalt
and a small amount of granitic contamination will hardly affect the basic
distribution.   It is only syntectics that occur in the central region whose
effects will be felt, and if the action takes place on the grand scale of
Daly's theory the tendency will be: (1) to absorb entirely the existing
modes; (2) to replace them by one dominant mode in the central region;
(3) to produce a typical asymmetric distribution; and (4) to reduce the
dispersion of the *whole* series.   None of these effects is, however, to be
observed, except a filling in of the central region when the actual distri-
bution is compared with the deduced law.   This investigation has pro-
ceeded on Daly's assumption that the primary rock is basalt, but even if
some other unknown parent were taken the tendency would be towards
the establishment of a simple asymmetric mode by this process—a remark-
able illustration of Harker's dictum that assimilation is a partial undoing
of the work of differentiation.

Bowen's Theory.—Bowen [1] considers with Daly that the parent magma
is basaltic in character, but he does not postulate other earth shells.   All
rocks have been derived from basalt by a process of differentiation.   Other
factors, such as magmatic mixing and syntexis, he discards as having had
little effect in the production of variety of types.   He regards the chief
factor in differentiation as fractional crystallization under the control of

[1] N. L. Bowen, Later stages in the evolution of igneous rocks, Journ. Geol.,
1915, vol. 23, supplement to no. 8.

gravity and earth movement, and rejects, like most petrologists, the operation of limited miscibility with the possible exception of the sulphide ores. All rocks, therefore, are derived by such 'crystallization-differentiation' from a primary basaltic earth-magma.

Now it has been seen that fractional crystallization is just that factor most likely to give a normal distribution of derivatives. Moreover, the analysis of the actual distribution has revealed a basic suite that is normal, has a mode at 52·5, and a standard deviation about 6. Whether or not we accept this particular curve as representing the natural basalt suite, rocks at the acid end are far too abundant to give any hope that the distribution will ever be fitted by a single normal curve with its mode at the basic end.

In this case also we may for comparison set out the relative frequencies of different rock types as obtained (I) from the basalt curve of fig. 1 alone, and (II) from the actual distribution :

		I.		II.
Basalt (52 %)	...	190	...	190
Peridotite (40 %)	...	62	...	60
Granite (73 %)	...	2	...	150

It is therefore seen that granite is actually seventy-five times as abundant as one might expect had it originated by differentiation from basalt in the upper crust.

Bowen, however, apparently considers that the production of granite may have happened in an early planetary stage, and that the ultrabasic pole is now sunk beyond reach. It may be this aspect that causes him to consider that his own results do not differ widely from Daly's. This point, however, is best considered in the next section.

4. Conclusions.

The study of the distribution of igneous rocks brings out the following relations :

(1) The existence of two strongly contrasted dominant rock types, namely, a basaltic and a granitic.

(2) The presence around each of these of a suite of derivatives distributed normally, i. e. so that small variations are more frequent than extremes.

(3) The divergence from this law in the region between the two dominant types.

(4) The greater dispersion of the basaltic suite when compared with the granitic.

(1) Relative to the visible and accessible igneous rock we must regard these two dominant magmas as primary—they were *intruded* into the crust and *there* through differentiation gave rise to all other types, except in so far as a portion of pre-Cambrian granite may yet be proved to be part of an original granitic cover. But Bowen claims that all granite has originated by crystallization-differentiation from basalt. It is not easy to gather from Bowen when he conceives this to have happened, but presumably at an early stage in the earth's history.

There are, however, considerable difficulties in the way of accepting this view. In the first place if mere crystal sorting were the agency, it is difficult to see why in the enormous space of time available this sorting has not been carried to completion so that only the end-products—say peridotite and granite—remain. Further, whilst the process may be applicable in the upper crust it is difficult to apply it to regions of much greater pressure in the light of recent experimental work. For instance, the effective operation of settlement requires that a large portion of the earth's crust must have been not merely liquid but fluid; yet Williamson has shown that the viscosity of kerosene increases enormously with pressure, so that at 12,000 atmospheres it is more viscous than vaseline.[1] If molten silicates increase in viscosity even at a much reduced rate, sinking of crystals must be very effectively hindered.

The only process so far as the preceding investigation goes that is capable of producing two completely contrasted types is limited miscibility. But, apart from the fact that it is open to the same objections as crystal sorting, there is no adequate experimental or other basis for applying the principle of limited miscibility to silicates. Moreover, it would entail the assumption of a parent of intermediate character, such as diorite.

The principle of the formation of composition gradients in the liquid phase under the action of gravity is not more hopeful, for the distribution should be rectangular, and anyhow the process would seem quite incapable of producing two sharply contrasted types.

There are, however, certain geochemical facts that may suggest a solution—namely, the correlation of the elements.[2] There is the association

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[1] E. D. Williamson, Change in the physical properties of materials with pressure, Journ. Franklin Inst., 1922, vol. 193, p. 509.

[2] H. S. Washington, The chemistry of the earth's crust, Journ. Franklin Inst., 1920, vol. 190, pp. 757–815 [Min. Abstr., vol. 1, p. 160].

of certain metals with particular rocks, e. g. tin with granites and platinum with peridotites. Further, these relations may be connected perhaps with the now well-established fact that granitic magmas carry a much larger proportion of mineralizers than the more basic types. Now according to his tidal-theory of the earth's origin Chamberlin considers it probable that at least portions of the atmosphere and of the hydrosphere were originally entangled with segregated planetesimals.[1] The processes of segregation, planetary stratification, and consolidation permitted an escape of much of the included volatile constituents, and naturally those layers near the surface would contain the residual mineralizers in greater abundance than those lying deeper. Again, the concentration of mineralizers in the later stages of granitic crystallization involves a concentration of highly siliceous material and of certain metals, as evidenced by the usual satellite suite of pegmatites. If we may extrapolate from these relations we may see in the escape, or upward concentration of the earth's volatile constituents, a process capable at the same time of extracting and carrying upwards towards the surface a large portion of silica and the alkalis giving an outer granitic magma, and leaving behind the heavier and more basic portion.[2]

It may be pointed out here that the frequency-distribution of the relative levels of the surface of the globe also exhibits two modes, one 100 metres above sea-level, and another 4,700 metres below sea-level. Wegener, in a brief account of his displacement theory, makes the following comment:[3] 'If the heights and depths had arisen through the elevation and depression of a single initial level, as geology has hitherto assumed, then we should expect statistics of level to show a grouping about one value. Instead of this there is a grouping about two values. So we must suppose that there are two initial levels, on which elevations and depressions have been superimposed; and this is only possible if these initial levels correspond to two different layers in the body of the earth.' It must surely be more than a mere coincidence that the results of geodesy and petrology are in apparent harmony in deducing two sharply contrasted shells of the outer crust—one of relatively light and the other of relatively heavy material.

(2) Granting, then, that the two primary magmas of the outer portion

[1] T. C. Chamberlin, The origin of the earth, Chicago, 1916, p. 165.

[2] J. W. Evans first advocated the importance of mineralizers in this type of differentiation ; see The genesis of igneous rocks, Sci. Progr., 1909, p. 318.

[3] A. Wegener, The origin of continents and oceans, Discovery, 1922, vol. 8, p. 115 and fig. 2.

of the earth resulted as an incident in the escape of volatile constituents, their eruption into the accessible portion of the earth's crust on relief of pressure gave rise to a suite of derivatives normally distributed around each of them. A probable cause of this distribution has been found in the process described by Bowen as ' crystallization-differentiation ', or the sorting of crystals under gravity control and earth movement.

(3) Departures from this ideal distribution are not really serious and affect only one region of the distribution. They consist in a partial filling in of the central region of the distribution. The existence of a third pole is possible, but does not effectively improve the fit. Syntexis would be a factor, but at the same time would make the left-hand curve asymmetric and shift the mode centrally, and so far the distribution shows no trace of such action. Magmatic mixing is capable of producing an ideal U-shaped distribution, and this is just the shape of the central part of the curve. And so far as there is a true cause, apart from the errors of sampling, of this central distribution, magmatic mixing is the most likely.

(4) It is noticeable in fig. 1 that the normal curve at the acid end is much narrower than that at the basaltic pole. The lesser dispersion of the acid end is reflected in the steeper slope of the distribution here—a point remarked upon by Harker. The accepted measure of dispersion is the 'standard deviation' (otherwise the mean square error), and the standard deviation of the basaltic curve is almost exactly twice that of the acid. Now the explanation of this difference must be found in the processes giving rise to the distribution. Either crystals may be segregated under the action of gravity, or residual liquor may be separated by earth movements. The latter is a process external to the magma, and, moreover, it must affect both suites equally in the long run. The effects of gravity on a crystallizing magma depend largely on properties of that magma, such as the order of separation ; viscosity ; differences in specific gravity in the constituents at any stage. So far as viscosity, which may be modified by the presence of mineralizers, is operative at all, it would be a restricting influence on differentiation of an acid magma as compared with a basic one. If the densities of various minerals are compared with that of melts, as in table I, it is seen that the only granitic minerals with relatively high densities are the micas, but this advantage is considerably offset since their flaky habit presents great surface to the liquid and hinders sinking. Otherwise the maximum difference between the densities of the solid phases and the liquid is about twice as great in basic as in acid rocks ; or nearly the same as the ratio of the dispersions. We

may conclude, therefore, that dispersions are determined mainly by the differences in densities, sorting effects being more marked the greater the difference; and partly by viscosity. It would appear, therefore, that crystallization-differentiation is competent not merely to account for the general type of distribution but also for the dispersions as represented by standard deviations (or more roughly by the relative slopes of the curves).

TABLE I.

DENSITIES.

Granite Rocks.			Basaltic Rocks.		
Muscovite	...	2·93	Fayalite	...	4·07
Biotite	...	2·90	Forsterite	...	3·22
Oligoclase	...	2·66	Augite	...	3·30
Quartz	...	2·65	Labradorite	...	2·71
Albite	...	2·64	Gabbro magma		
Orthoclase	...	2·56	at 1000° C.	...	2·75
Granite magma					
at 1000° C.	...	2·40			

Note.—The densities of the minerals are after Miers (Mineralogy) and of the magmas after Daly (Igneous Rocks).

5. *Summary.*

1. The actual distribution of igneous rocks as revealed by that of silica in analyses can be shown to consist of two semi-normal curves of error situated at its extreme ends with a U-type distribution in the central part.

2. The distribution can be fitted with two normal curves of error determined by the shape of the end-curves of the actual distribution, revealing a law such that all visible igneous rocks are normally distributed about two types—a basalt and a granite.

3. The divergence from this law in the central region is possibly due in part to errors of sampling, and in part to magmatic mixing.

4. The primary types arose during an early planetary stage. The acid external layer may have arisen under the influence of escaping volatile constituents, which concentrated upwards much silica and alkalis. Neither the syntectic-differentiation theory of Daly nor the one-magma theory of Bowen is capable of accounting for the distribution.

5. The normal suites with their characteristic dispersion can be produced by 'crystallization-differentiation' as defined by Bowen.