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CHEMISTRY OF IGNEOUS ROCKS
I. DIFFERENTIATION INDEX*

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ABSTRACT. Recent experimental studies corroborate the evidence Bowen used in 1937 to demonstrate that fractional crystallization of complex magmas produces liquids which move toward and, for all practical purposes, eventually reach the system SiO_2–$NaAlSiO_4$–$KAlSiO_4$, petrogeny's residua system. In a volcanic rock series the distance a given magma has travelled toward this goal can be quantitatively measured by calculating the norm and summing the constituents of petrogeny's residua system; this value is called the differentiation index. It is a useful coordinate for variation diagrams and is a measure of the "basicity" of a rock.

A series of frequency distribution diagrams have been prepared from 5000 analyses in Washington's Tables. Using these diagrams, any rock analysis can be compared at a glance with all the analyses and any deviations from the "average" can readily be seen.

INTRODUCTION

The importance of the system SiO_2–$NaAlSiO_4$–$KAlSiO_4$ in igneous petrology was pointed out long ago by Bowen and although his deductions have been generally accepted, no particular use has been made of these important relations. This paper is the first of a series which will consider some applications of the concept of petrogeny's residua system to petrologic problems. To a large extent these papers will represent the results of the authors' attempts to provide a systematic view of the chemistry of igneous rocks for students.

In 1937 Bowen published a paper, "Recent high-temperature research on silicates and its significance in igneous geology", in which he discussed the nature of the final residual liquids resulting from fractional crystallization of silicate magmas. He demonstrated with the aid of six experimentally determined systems that the residual liquid formed by fractional crystallization is enriched in alkali-alumina silicates, whether the other components of the systems are lime-alumina silicate, lime-magnesia silicate, or iron silicate, and he concluded that the residual liquid from fractional crystallization in a complex system such as a magma will show this same character of enrichment in alkali-alumina silicates. He further pointed out that the system SiO_2–$NaAlSiO_4$–$KAlSiO_4$ is the goal toward which all magmatic liquids move on fractional crystallization. This system, embracing the compositions of the rock-forming minerals, quartz, orthoclase, albite, nepheline, leucite, and kalsilite, is the end of the road for fractional crystallization except under very special circumstances and, like Rome, all roads lead to it.

The fact that petrogeny's residua system is a goal toward which all magmas will move, but cannot pass, on fractional crystallization gives it special significance in that the proportion of the constituents of this system present

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in a rock is a measure of the "basicity"[1] of the rock. For example if a rock contains 50 percent normative pyroxene and 50 percent normative albite + orthoclase + quartz, it is exactly half-way between petrogeny's residua system and a pyroxenite. The same can be said of a rock consisting of 50 percent normative pyroxene and 50 percent normative albite + orthoclase + nepheline. If we now imagine that petrogeny's residua system is the base of a tetrahedron and the top apex represents all the mafic constituents summed together, the distance from the top apex to a point giving the composition of a rock is a measure of the amount of the constituents of petrogeny's residua system in the rock and is also a measure of the basicity of the rock. This quantity, the differentiation index (D. I.), is the sum of the normative percentages of quartz, orthoclase, albite, nepheline, leucite, and kalsilite and we will now consider the application of this quantitative measure of the basicity of a rock to various petrologic problems. The D. I. may be the same, whether the rock is alkaline or acid, and it is not a measure of the silica saturation.

Since the general concept of the differentiation index is based on the relations proposed by Bowen, it is desirable to review the evidence he presented in 1937, together with recent results of studies on pertinent systems.

PETROGENY'S RESIDUA SYSTEM

To considerable extent the low melting temperature of the alkali feldspars and mixtures of these feldspars with silica on the one hand and with nepheline on the other, are responsible for the "residua" nature of the system SiO_2–$KAlSiO_4$–$NaAlSiO_4$. The addition of any considerable amount of MgO, FeO, or CaO, the common oxides of the mafic igneous rocks, raises the liquidus temperatures drastically. The binary systems $CaMgSi_2O_6$ (diopside) – $NaAlSi_3O_8$ (albite) (Bowen, 1915), Fe_2SiO_4 (fayalite)–$NaAlSi_3O_8$ (albite) (Bowen and Schairer, 1936), Mg_2SiO_4 (forsterite) – $NaAlSi_3O_8$ (albite) (Schairer, 1957), and $CaAl_2Si_2O_8$ (anorthite) – $NaAlSi_3O_8$ (albite) (Bowen, 1913) illustrate this relationship (fig. 1). Crystallization of liquids in all these systems will enrich the liquid in the constituents of alkali feldspars and will impoverish the liquid in the constituents of anorthite, diopside, fayalite, or forsterite. In the system $NaAlSi_3O_8$–$CaAl_2Si_2O_8$ the low melting liquid has the composition of pure albite; in albite-diopside the liquid contains about three percent of the constituents of diopside; in albite-fayalite about 15 percent fayalite, and in albite-forsterite about three percent forsterite. Similar

[1]It has been found convenient to use the following adjectives to describe the differentiation index and the silica content of rocks:

Undersaturated		
(Alkaline)	:	Having a relatively low silica content compared with other rocks of the same differentiation index. Shand (1943) introduced saturation for his modal classification of igneous rocks. Here we are using the term in a somewhat different sense by considering normative rather than modal constituents.
Oversaturated		
(Silicic)	:	Having a relatively high silica content compared with other rocks of the same differentiation index.
Basic	:	Having a relatively low differentiation index, i. e., below 50.
Salic	:	Having a relatively high differentiation index, i. e., above 50.

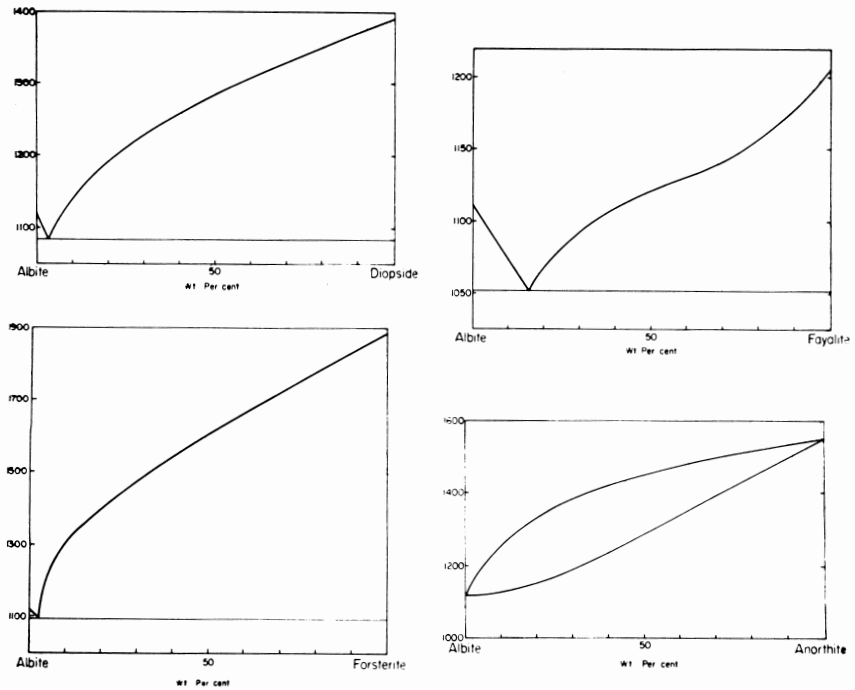

Fig. 1. Binary phase equilibrium diagrams illustrating that the final liquid on crystallization is rich in the alkali-alumina-silicate, albite.

relations undoubtedly occur in other binary systems such as $MgSiO_3$ (enstatite)–$NaAlSi_3O_8$ (albite), $CaSiO_3$ (wollastonite)–$NaAlSi_3O_8$ (albite), etc.

Binary systems containing potash feldspar instead of albite show similar relations but the incongruent melting of potash feldspar complicates the presentation of binary equilibria. The same principle can, however, be illustrated by the system $KAlSi_3O_8$–$CaAl_2Si_2O_8$–H_2O at 5000 bars water vapor pressure (Yoder, Stewart, and Smith, 1957). Figure 2 is a projection of the liquidus relations in this system onto the potash feldspar-anorthite side of the isobaric prism; here the temperatures have been lowered sufficiently by water vapor to permit potash feldspar to crystallize directly without the appearance of leucite. Crystallization in this system will produce a liquid carrying at least 88 percent of the constituents of potash feldspar. In natural magmas other constituents, in addition to water, (i. e., silica, nepheline, etc). will act to lower the liquidus and solidus temperatures below the leucite stability field.

Ternary systems, in which one of these silicates is added to silica plus one of the alkali-alumina-silicates, show that with crystallization an even more drastic enrichment of the liquid in these low melting compositions takes place. Figure 3 (Schairer, 1954), for example, shows that crystallization will give rise to a residual liquid containing less than two percent of the constituents of forsterite. It is interesting to note that forsterite (or enstatite) will crystallize *first from a liquid containing only two percent forsterite.* In a discussion of

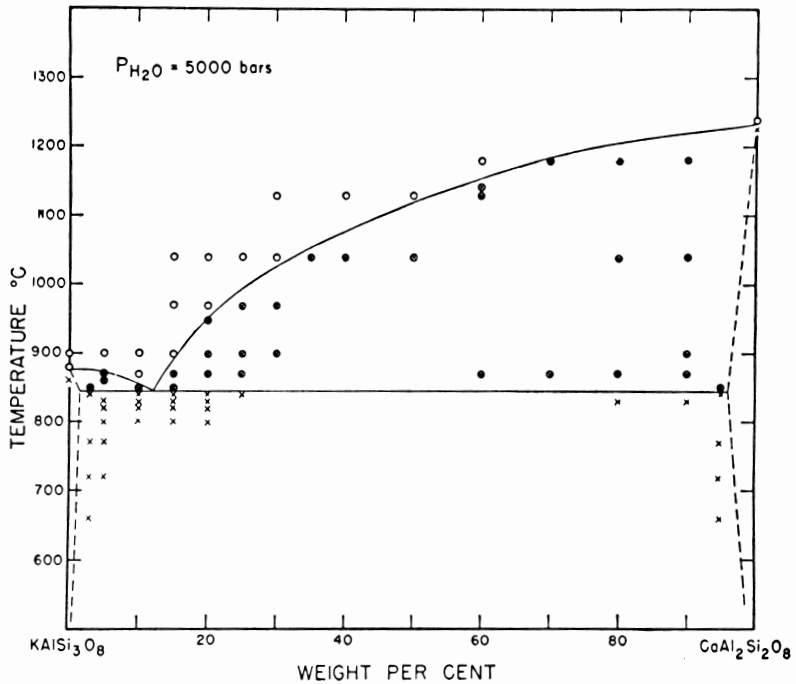

Fig. 2. Isobaric (5000 bars) projection of the phase relations (Yoder, Stewart, Smith, 1957) in the ternary system $KAlSi_3O_8$–$CaAl_2Si_2O_8$–H_2O onto the anhydrous TX plane. The residual liquid on isobaric crystallization will contain more than 88% orthoclase.

crystallization in the system $KAlSi_2O_6$–$CaMgSi_2O_6$–SiO_2 Schairer and Bowen (1938) noted:

> Pyroxene (diopside) is removed first, almost quantitatively, on cooling and crystallizing, leaving a low-melting liquid whose composition approaches a mixture of potash feldspar and silica. . . .

If diopside is replaced by anorthite, the relations are essentially the same (Bowen, 1937), anorthite crystallizes first from a liquid with an anorthite content as low as three percent. This tendency to give compositions, on crystallizing, that are essentially orthoclase plus silica is found even when additional alumina is present, and in the system $Mg_2Al_4Si_5O_{18}$–$KAlSi_2O_6$–SiO_2 (Schairer, 1954) (fig. 4) the relations along the orthoclase-silica side line are essentially the same as when forsterite, anorthite, or diopside is present.

Data for only one of the corresponding systems with soda feldspar instead of potash feldspar has been published: the $Mg_2Al_4Si_5O_{18}$–$NaAlSi_3O_8$–SiO_2 system (Schairer, 1957) (fig. 5). Here the same enrichment of the liquid in feldspar constituents and silica takes place on crystallization and it is virtually certain that similar relationships will be found in the other systems involving soda feldspar.

Two other systems involving albite have been studied: Fe_2SiO_4–$NaAlSiO_4$–SiO_2 (Bowen, 1937), and Mg_2SiO_4–$Mg_2Al_4Si_5O_{18}$–$NaAlSi_3O_8$ (Schairer, 1957)

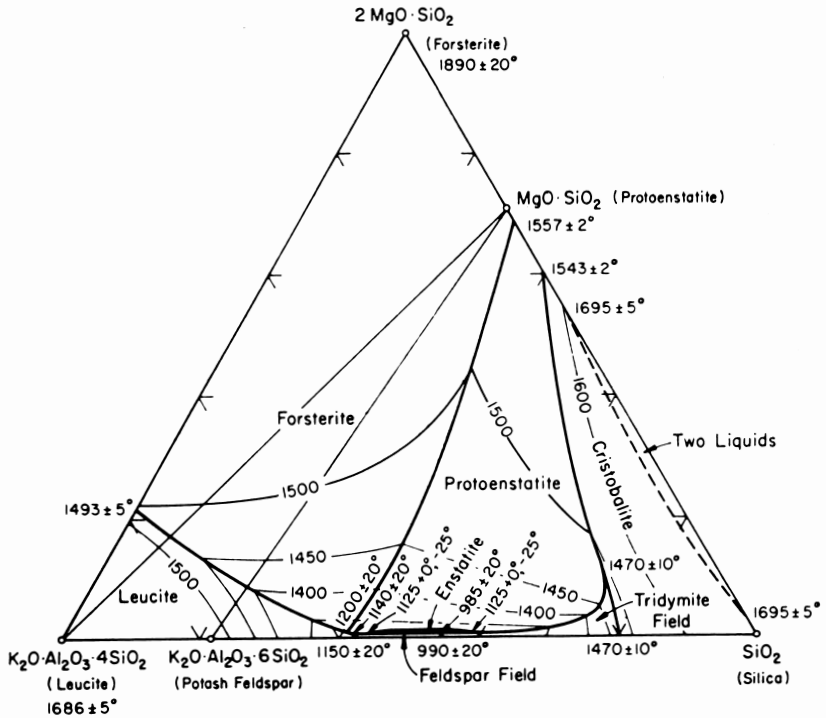

Fig. 3. Phase equilibrium diagram (Schairer, 1954) to illustrate the pronounced enrcihment of the liquid in orthoclase on crystallization in the system Mg_2SiO_4–$KAlSi_2O_6$–SiO_2.

(fig. 6). In both, the enrichment in albite on crystallization is pronounced and in the latter the final liquid is essentially albite in composition.

In a recent study of the quaternary system K_2O–MgO–Al_2O_3–SiO_2 Schairer (1954) demonstrated in a striking fashion that Bowen was justified in extrapolating from ternary to more complex compositions. In the portions of this system which are of petrologic interest, crystallization will cause the liquid to proceed to a composition essentially the same as discussed above—a mixture of orthoclase and silica. The studied portion of the quaternary systems may be divided into two subsidiary quaternary volumes, leucite-corundum-spinel-silica and leucite-forsterite-spinel-silica. which make up the bulk of the larger system. All liquids in the volume leucite-corundum-spinel-silica will, on crystallization, change composition toward a quaternary eutectic and in the volume leucite-forsterite-spinel-silica crystallization also moves the liquid toward a quaternary eutectic; these two eutectics are very close together in composition and both can be considered to consist essentially of a mixture of orthoclase and silica. The temperature of the eutectics is 960°C ± 20, the lowest temperature at which a liquid appears in the two quaternary systems.

It is virtually certain that the phase relations in the system Na_2O–MgO–Al_2O_3–SiO_2 are similar, and it is no great extrapolation to a five-component system in which both soda and potash are present; in these systems the mag-

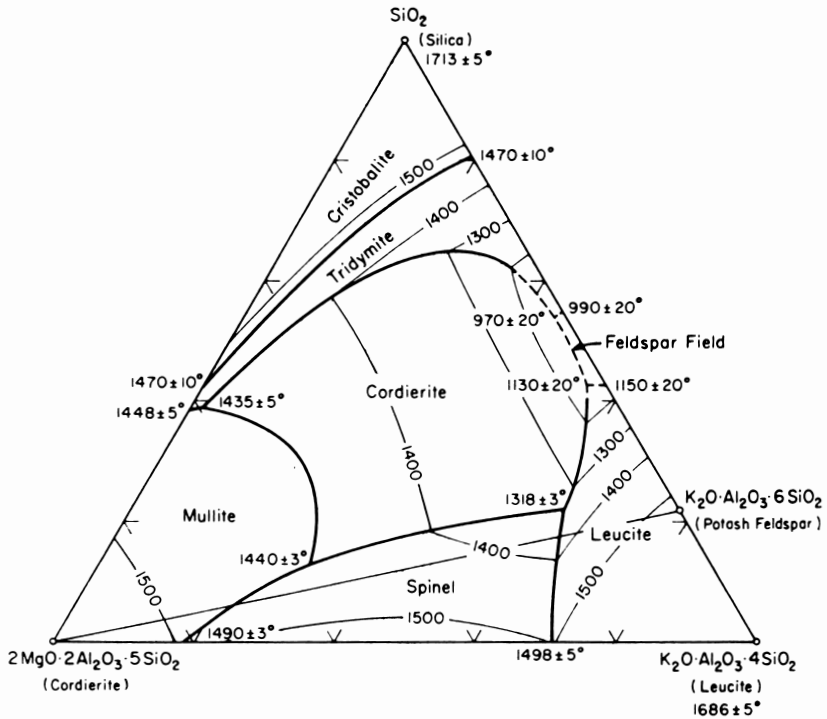

Fig. 4. Ternary phase equilibrium diagram (Schairer, 1954) for the system $Mg_2Al_4Si_5O_{18}$–$KAlSi_2O_6$–SiO_2. Note the low melting composition near the feldspar-silica eutectic.

nesia would be almost quantitatively removed on crystallization just as in the system studied by Schairer. This quantitative removal of the high melting substances by crystallization is, then, no magic process that cannot be understood because it is impossible in the laboratory to work with and understand the phase relations when more than five or six components are present; rather, it is a process that must go on in the magmas just as in the simple systems which have been studied under measured and controlled conditions in the laboratory.

Bowen (1937) demonstrated the principle of petrogeny's residua system with six experimentally studied systems: we have looked at nine additional systems and it has been found that his deductions regarding the consequences of crystallization hold for all of these systems.

The rocks themselves provide evidence that crystallization produces liquids richer in the constituents of petrogeny's residua system than the rock as a whole. Figure 7 has been prepared to show this relationship in a series of porphyritic rocks in which the aphanitic or glassy groundmass and the rock as a whole have been separately analyzed. The D. I. has been plotted against silica to show that *the groundmass is, without exception, richer in the constituents of petrogeny's residua system than is the rock as a whole.*

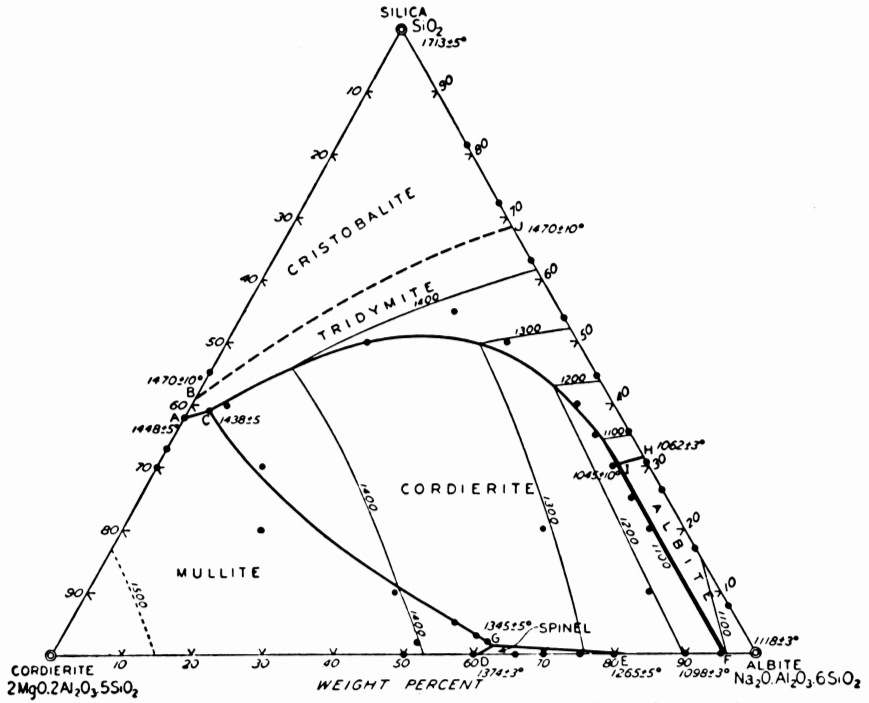

Fig 5. Phase diagram for the system $Mg_2Al_4Si_5O_{18}$–$NaAlSi_3O_8$–SiO_2 (Schairer, 1957). Note the low melting compositions near the feldspar-silica eutectic.

THE DIFFERENTIATION INDEX

The differentiation index is the sum of the weight percentages of normative quartz + orthoclase + albite + nepheline + leucite + kalsilite. No more than three of these normative minerals will appear in any given norm, thus the *differentiation index is simply the sum of the percentages of three normative minerals.* These are the salic constituents of the C.I.P.W. norm with one major exception, anorthite, and several minor exceptions, zircon, corundum, halite, thenardite, sodium carbonate, etc. In the present study normative anorthite, zircon, and corundum are considered "basic constituents" of the rock and, in view of the experimental work cited above, there is no doubt that anorthite should be so treated; the case for zircon and corundum is not as strong, but we feel that they are more appropriate as femic constituents than as salic. Normative thenardite, halite, and sodium carbonate occur in insignificant amounts and no serious error is introduced by ignoring them for the present study.

In a rigorous calculation of the differentiation index the norm should be summed to 100 percent excluding halite, thenardite, sodium carbonate, sodium metasilicate, potassium metasilicate, water, and other minor constituents; in the present survey of the norms in Washington's Tables this has not been done because the error is negligible in all but a few analyses and the labor involved in making the correction is considerable.

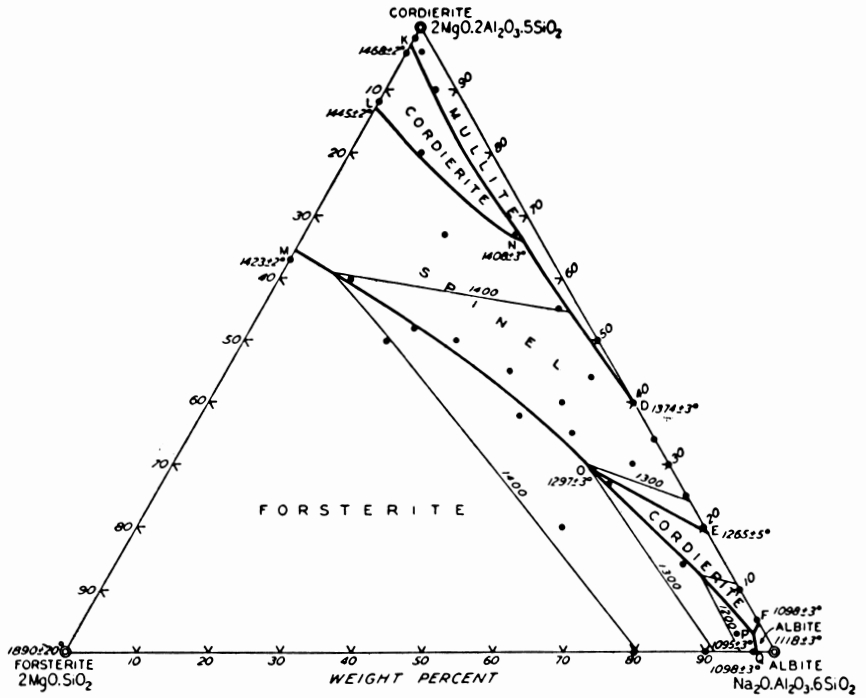

Fig. 6. Phase equilibrium diagram for the system $Mg_2Al_4Si_5O_{18}$–Mg_2SiO_4–$NaAlSi_3O_8$ (Schairer, 1957). The low melting compositions are rich in albite.

The differentiation index for the major igneous rocks of Daly's (1914) averages are as follows:

	D.I.		D.I.
Alkali granite	93	Alkali rhyolite	91
Granite	80	Rhyolite	88
Granodiorite	67	Quartz latite	68
Diorite	48	Andesite	56
Gabbro	30	Basalt	35
Olivine gabbro	27	Olivine diabase	30
Peridotite	6	Picrite	12

FREQUENCY DISTRIBUTION OF THE DIFFERENTIATION INDEX OF IGNEOUS ROCKS

The differentiation indices of the 5000 superior analyses of igneous rocks in Washington's Tables are shown in the histogram of figure 8. The maximum at D.I. = 87 represents the very large number of analyses of granitic rocks. Perhaps the most interesting feature is the uniform number of analyses in the range D.I. = 70 to 30, the range of the intermediate and basic igneous rocks. This diagram should be compared with the silica frequency histogram prepared by Richardson and Sneesby (1922) which has been widely reproduced in petrologic literature. The silica histogram shows two maxima, one at 52.5

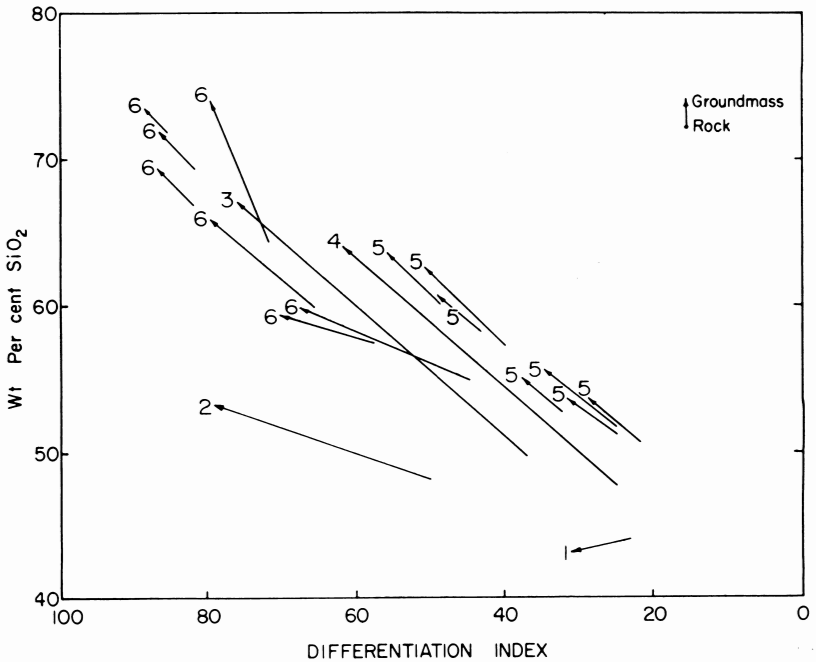

Fig. 7. Silica-differentiation index diagram illustrating the compositions of groundmass and the entire rock in some porphyritic volcanic rocks 1 (Fenner, 1935), 2 (Lacroix, 1907), 3 (Walker, Vincent, Mitchell, 1952), 4 (Vincent, 1950), 5 (Kuno, 1950), and 6 (Larsen, 1956).

percent silica, and one at 73.0 percent silica, and Daly (1933, p. 41) has used this to support his contention that

> The igneous rocks of the globe belong chiefly to two types: granite and basalt . . . . Richardson and Sneesby have again proved it, by a method quite different from that just outlined.

If Daly's assertion is correct, the above histogram should show a minimum in the range D.I. = 70 to 50 (the compositional range of the intermediate rocks) since the differentiation index is a good measure of the basicity of an igneous rock. The apparent discrepancy arises from the fact that the silica content of alkaline rocks (i.e., nepheline syenites, phonolites, syenites, etc.) is essentially the same as that of basalts and gabbros and the maximum in the silica histogram at 52.5 percent silica is misleading in this respect. Therefore the Richardson and Sneesby histogram should not be interpreted as indicating that granites and basalts are the two chief types of igneous rocks. In volume percent, the intermediate rocks are by far the most abundant.

OXIDE DISTRIBUTION AND THE DIFFERENTIATION INDEX

Inasmuch as the differentiation index is a measure of the basicity of an igneous rock, it is an ideal quantity for illustrating variations in the chemistry of the igneous rocks. Accordingly, a series of frequency diagrams showing the oxide variations in igneous rocks as a function of basicity have been prepared

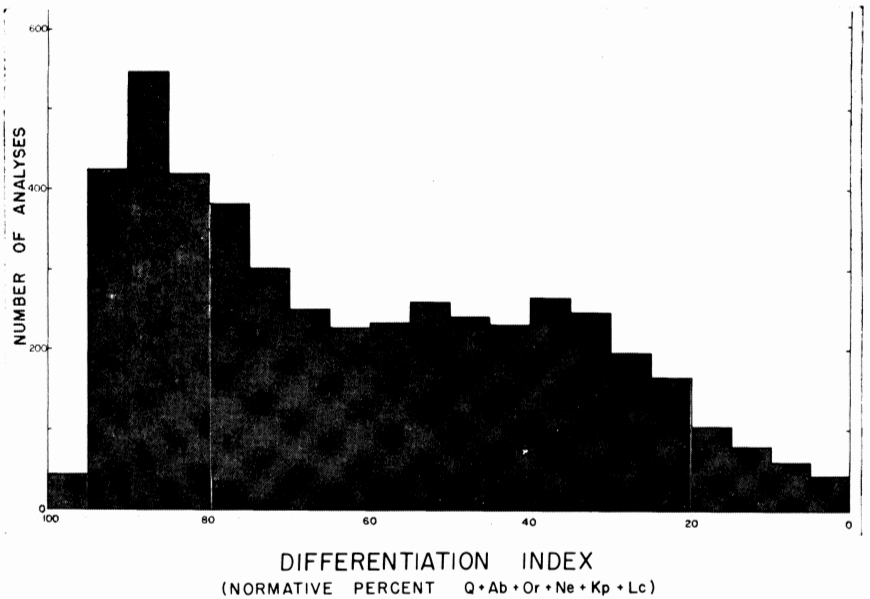

Fig. 8. Histogram illustrating the distribution of the differentiation index for the 5000 analyses in Washington's Tables.

(figs. 8-15) by plotting the oxide percentage against the differentiation index for 5000 analyses in Washington's Tables. As it is not convenient to reproduce these diagrams directly, they have been contoured by the usual petrofabric technique in order that the frequency distribution of analyses can be seen at a glance. All analyses fall within the outermost contour. The counting area was 0.16 percent instead of the usual one percent area used in petrofabric work; the area was square since it was centered on rectangular diagrams. The small counting area is necessary because the concentrations of points are very high (some 0.16 percent areas contained over 200 points) because much of each diagram is necessarily void of points.

In all the diagrams, with the exception of silica, the area between the outermost and the next higher contour contains from 1 to 25 points in a 0.16 percent area, the next area contains 26-50 points, the next 51-75, then 76-100, 101-125, 126-150, 151-175, etc. In the silica diagram two extra contours are included because of the greater spread in SiO_2 values. These contours represent 1-12, 13-25, 26-38, and 39-50 points in a 0.16 percent area.

Silica distribution.—The maximum concentration of this diagram (fig. 9) falls along a relatively straight line running from approximately 37 percent at D.I. = 0 to 80 percent at D.I. = 100. Two maxima occur on the diagram, one at a D.I. = ca. 38 and a silica content of about 52 (corresponding to the basalts and gabbros) and the other, a very strong maxima, at D.I. = ca. 90 and a silica content of 75 percent (corresponding to the granites and rhyolites). The "ridges" or trends of the maxima are along the compositions for the silicic rock series. As the nepheline-bearing rocks are low in silica, they are well

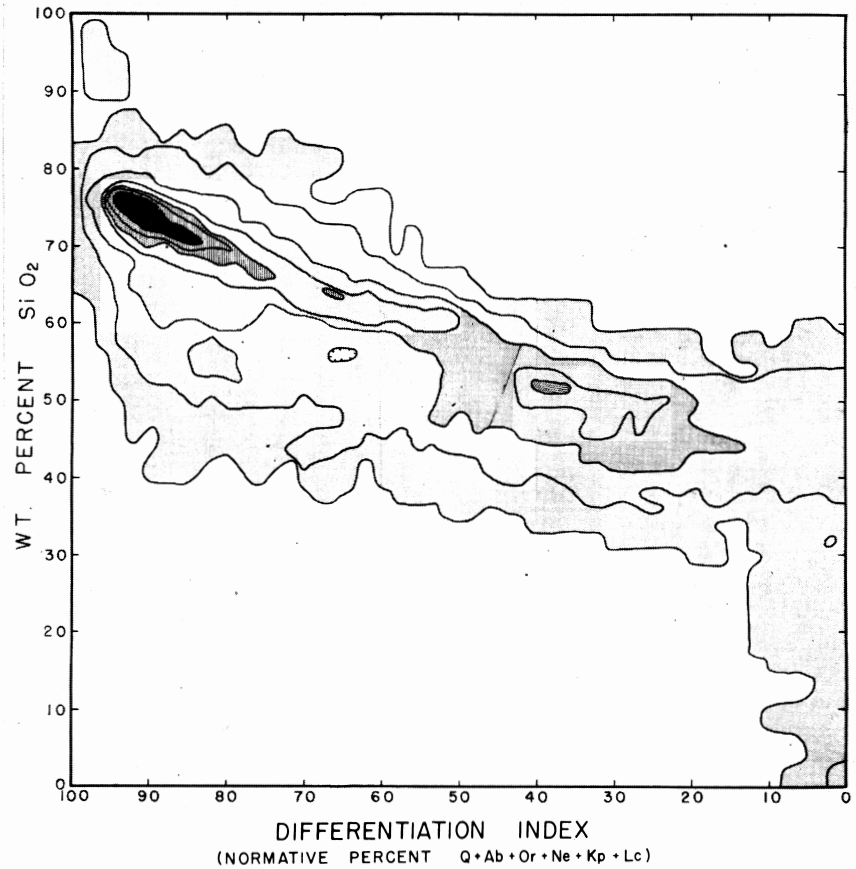

Fig. 9. Contoured diagram showing the silica vs. differentiation index for the 5000 analyses in Washington's Tables. See text for details.

separated from the silicic rocks on this diagram. The small subsidiary maximum at D.I. = 80, silica = 55 probably represents the relatively large number of nepheline syenites and phonolites which have been analyzed.

The silica-D.I. diagram is a useful means of distinguishing undersaturated from oversaturated rocks. If a line is drawn from the silica content of albite at D.I. = 100 (68.7% silica) to the silica content of anorthite at D.I. = 0 (43.2% silica), those analyses falling below the line are largely undersaturated whereas those above the line are oversaturated (fig. 10). This is obvious in figure 10 where the silica content of the minerals of petrogeny's residua system are plotted along the D.I. = 100 coordinate and the silica content of the femic normative minerals are along the D.I. = 0 coordinate. Here a saturated rock would be expected to fall in or near the area albite-orthoclase-anorthite and when the rock is largely a mixture of these constituents (as in the case of a trachyte, syenite, or anorthosite), it will fall in this area. Undersaturated rocks will then generally fall below this dividing line because the undersatu-

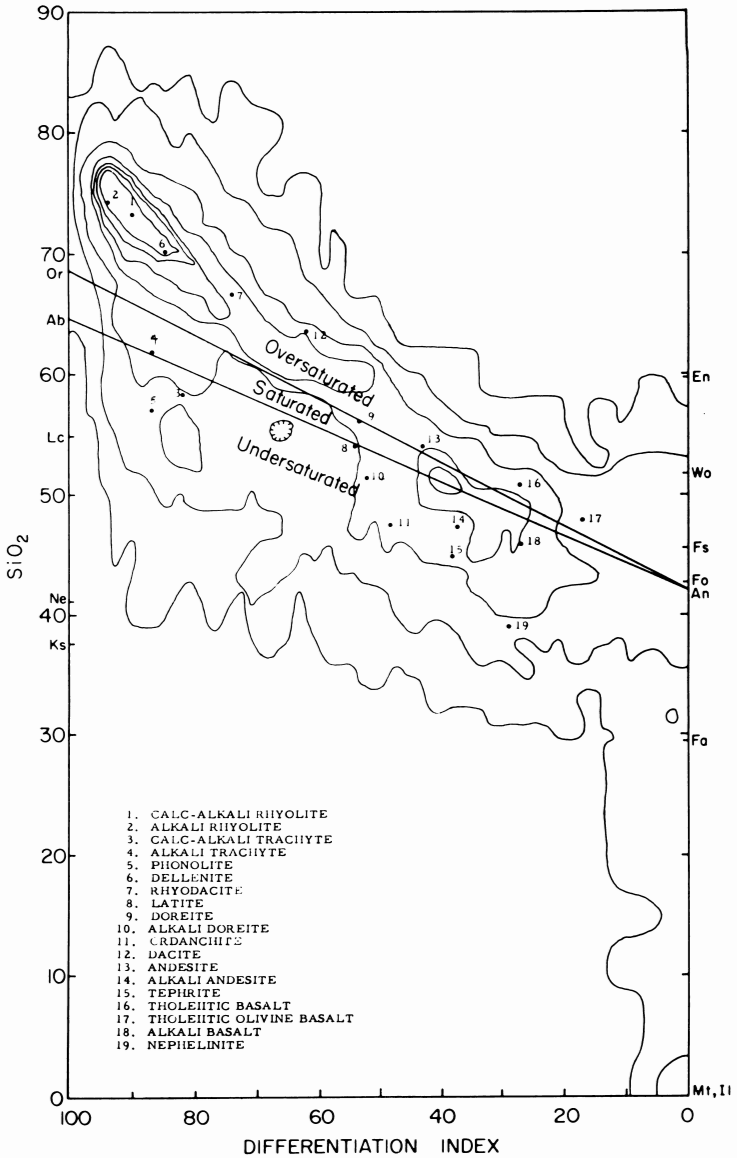

Fig. 10. Contoured silica-differentiation index diagram illustrating the silica content of normative Or, Ab, Lc, Ne, Ks, En, Wo, Fs, Fo, An, Fa, Mt, and Il together with Nockold's averages for some extrusive rocks (Nockolds, 1954). Oversaturated rocks will generally fall above the line from Or to An whereas undersaturated rocks will fall below this line.

rated minerals leucite, nepheline, kalsilite, and fayalite carry less SiO_2 than do the feldspars, whereas most oversaturated rocks will fall above the line.

Alumina distribution.—The distribution of alumina in 5000 analyses of Washington's Tables is shown in figure 11. In contrast to the silica diagram the alumina frequency distribution has only one strong maximum. Probably this maximum represents the alumina of the granites and rhyolites.

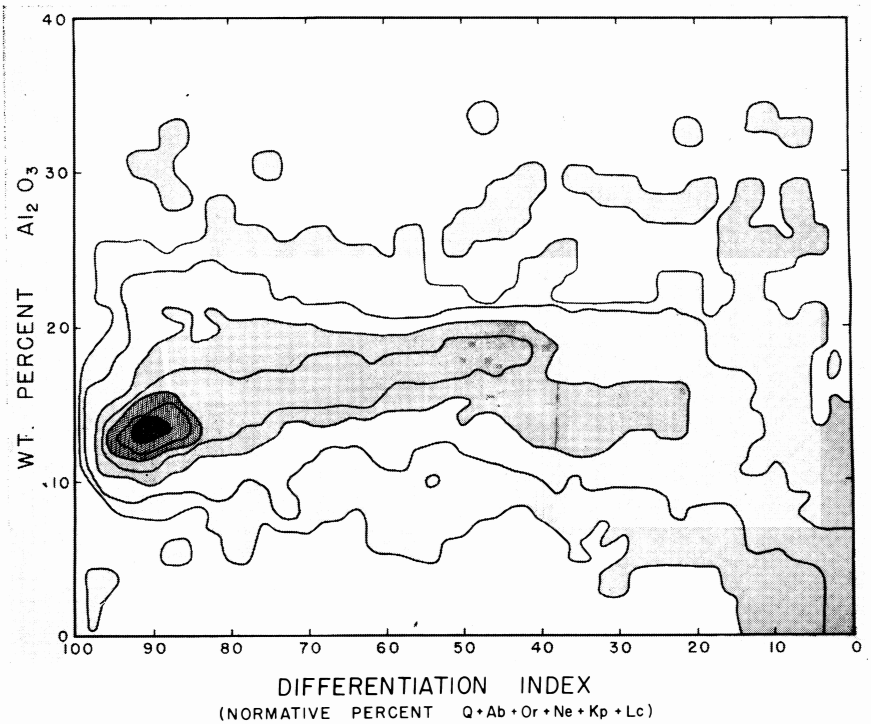

Fig. 11. Contoured diagram showing the distribution of the Al_2O_3 content of the 5000 analyses of Washington's Tables as a function of differentiation index.

Ferric oxide distribution.—Ferric oxide has a wide range of variation in all rock types, the greatest number of analyses falling at approximately 2.5 percent Fe_2O_3 throughout the range of basalt to granite (fig. 12). The maximum region is elongated almost parallel to the abscissa. Presumably the Fe_2O_3 is removed at a constant rate from magmatic liquids during crystallization throughout the basalt to rhyolite compositional range.

Lime, magnesia, and ferrous oxide distribution.—Figures 13, 14, and 15 show the distribution of these three oxides of the analyses in Washington's Tables. In all cases there is a strong maximum near D.I. = 90 with an elongation of the maximum toward higher CaO, MgO, and FeO as the composition becomes more basic. Such a general relation can be expected since these oxides are largely responsible for the basic nature of the gabbros, basalts and peridotites. The change is related to the fact that these constituents are continuously removed from the basic magmas during crystallization and there is no tendency for concentration in the liquid during fractionation.

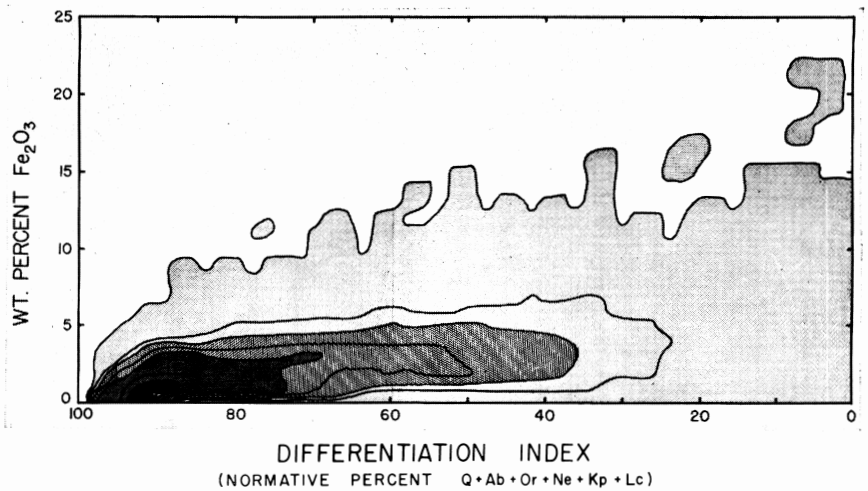

Fig. 12. Contoured diagram showing the distribution of the Fe_2O_3 content of the 5000 analyses of Washington's Tables as a function of differentiation index.

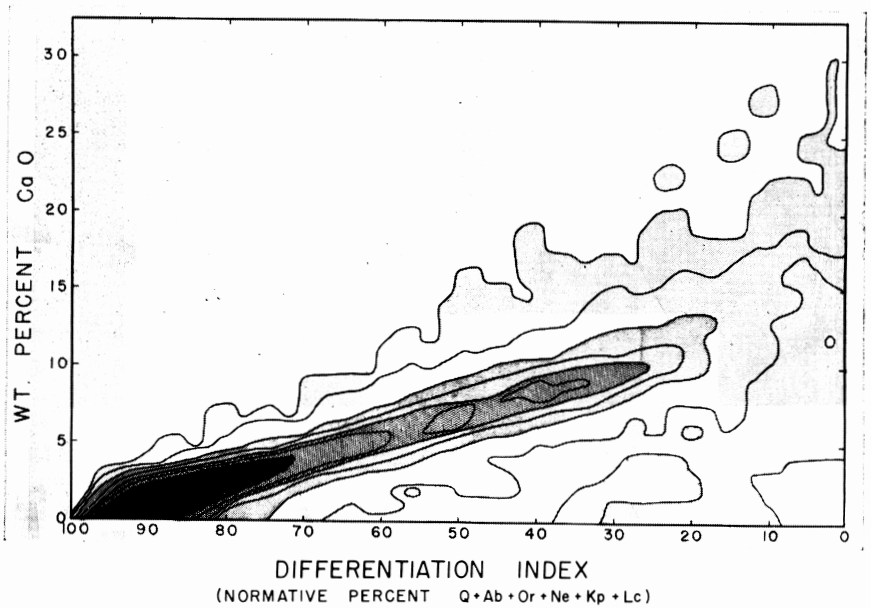

Fig. 13. Contoured diagram showing the distribution of the CaO content of the 5000 analyses of Washington's Tables as a function of differentiation index.

Alkali distribution.—The distributions of K_2O and Na_2O are shown in figures 16 and 17. The most interesting feature is the contrast between soda and potash. The maximum for soda indicates that in most rocks the soda content is remarkably constant whereas there is a steady increase in the potash

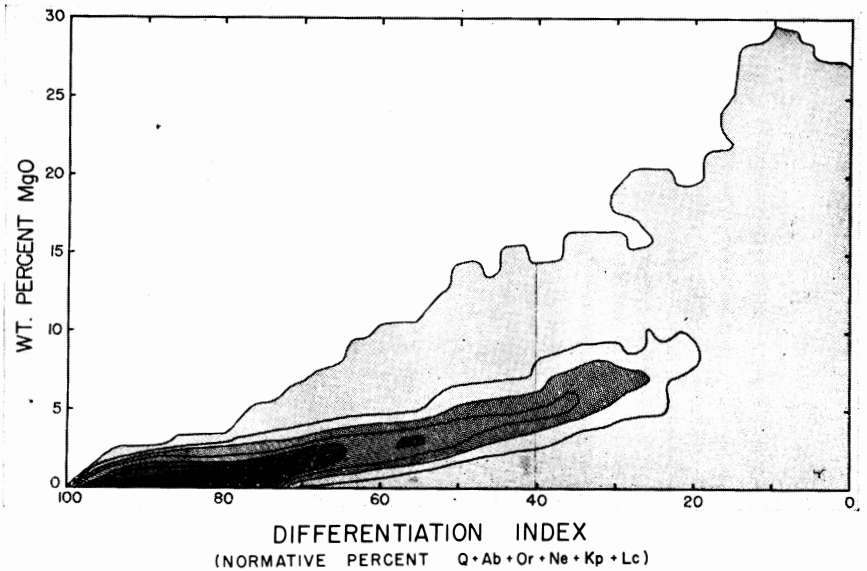

Fig. 14. Contoured diagram showing the distribution of the MgO content of the 5000 analyses of Washington's Tables as a function of differentiation index.

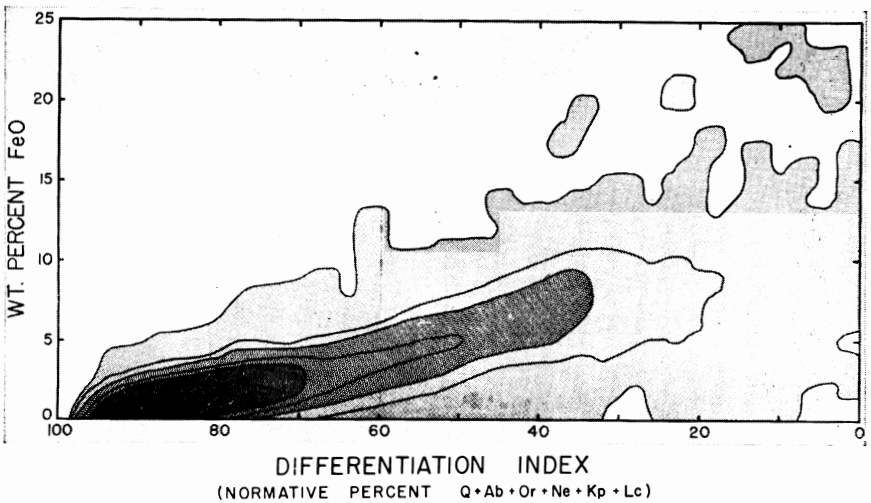

Fig. 15. Contoured diagram showing the distribution of the FeO content of the 5000 analyses of Washington's Tables as a function of differentiation index.

content with increasing D.I. This is a result of the fact that soda is continually taken from magmatic liquids during crystallization as a component of plagioclase feldspar and amphiboles, while potash is generally held in the liquid until alkali feldspar crystallizes or until the water content is sufficiently high to precipitate biotite.

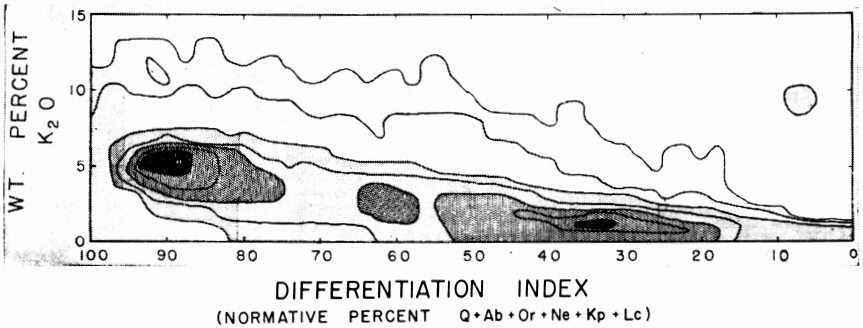

Fig 16. Contoured diagram showing the distribution of the K_2O content of the 5000 analyses of Washington's Tables as a function of differentiation index.

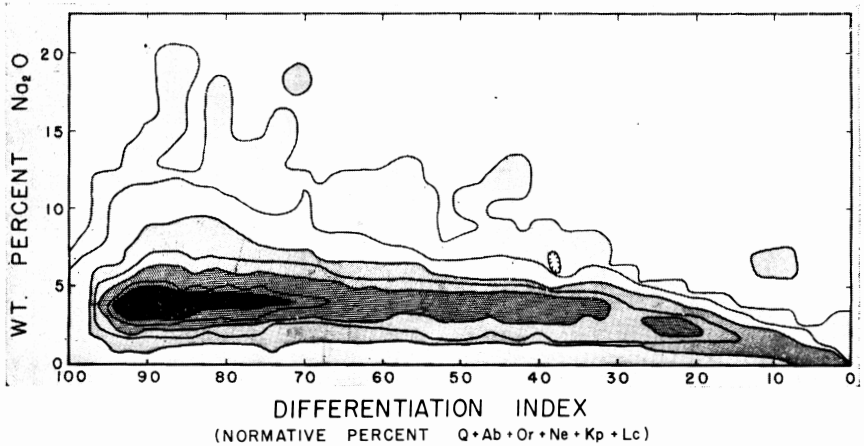

Fig. 17. Contoured diagram showing the distribution of the Na_2O content of the 5000 analyses of Washington's Tables as a function of differentiation index.

The potash diagram has two maxima, one corresponding to basaltic and gabbroic rocks, and the other (D.I. = 90) to granitic and rhyolitic rocks; the soda distribution has only one maximum in the range D.I. = 75-95.

Summary.—On the basis of 5000 analyses in Washington's Tables it can be said that as the D.I. increases, (1) silica and potash increase continuously in the majority of analyses, (2) lime, magnesia, and ferrous oxide decrease continuously throughout the series, (3) there is little or no change in soda and ferric oxide content, although the former decreases in the ultrabasic rocks and the latter decreases sharply at the salic end of the series, and (4) the silica and potash diagrams show two maxima, one near D.I. = 90, and the other at D.I. = 35-38 corresponding, presumably, to the granites and rhyolites on the one hand, and to the gabbros and basalts on the other.

VARIATION DIAGRAMS

The differentiation index is a natural quantity to use for variation diagrams of rock series since it is based on experimental data corroborated by

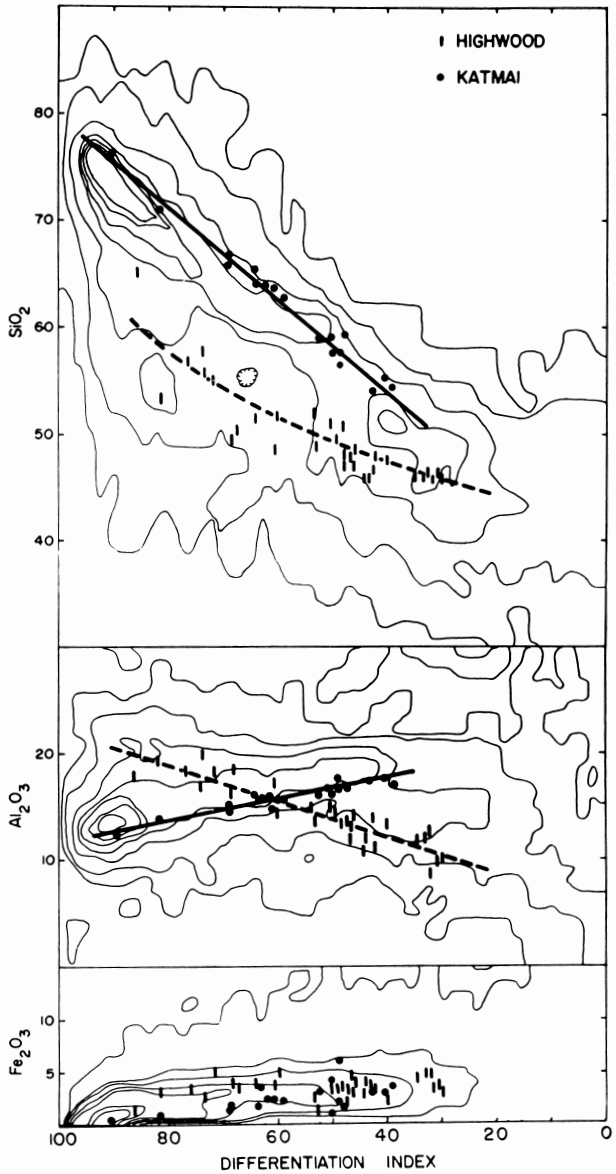

Fig. 18A

Fig. 18. Contoured diagrams of oxide vs. differentiation index on which analyses of rocks from the Highwood, Montana, and Katmai, Alaska, petrographic provinces have been superimposed. The analysis of the Katmai rocks are "average" except for K_2O whereas the analyses of the Highwood rocks do not fall near the maxima and are unusual for all the oxides.

chemical studies of igneous rocks and is a measure of the basicity of a rock. In general, petrologists have used silica as the abscissa of their variation dia-

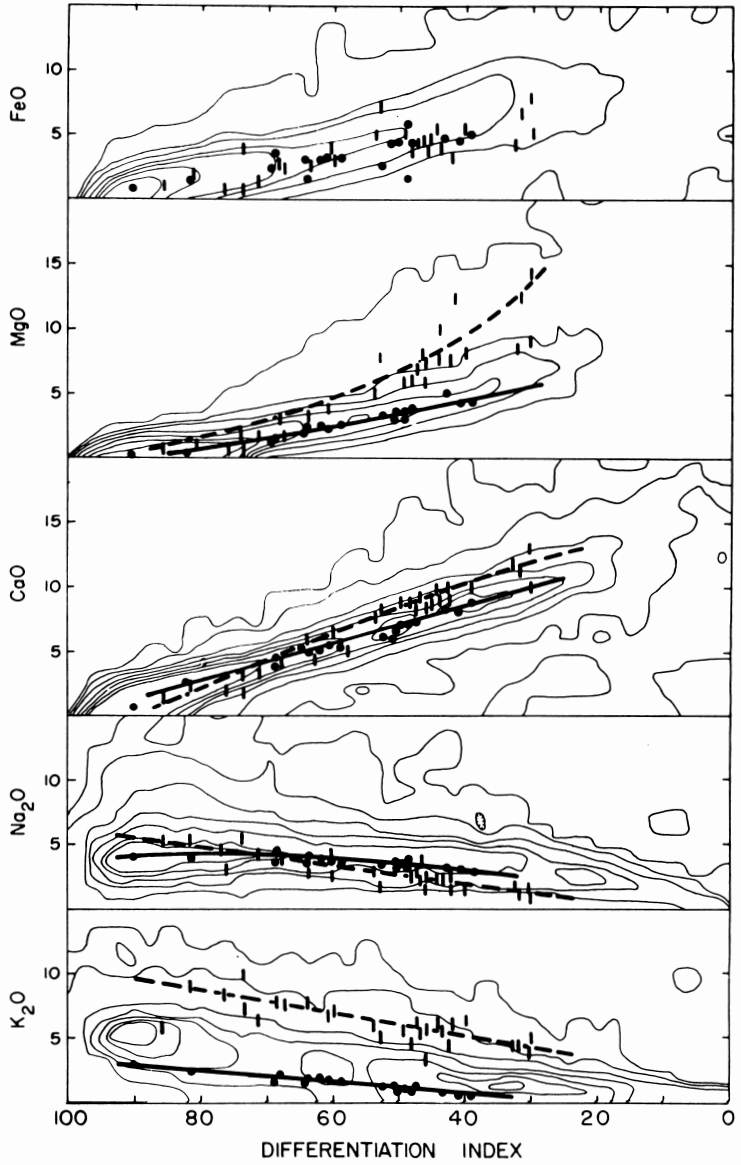

Fig. 18B

grams although many have realized that it has serious disadvantages for this purpose. Attempts to use other quantities for variation diagrams such as the Larsen index ($1/3SiO_2 + H_2O - Fe - MgO - CaO$) have not been universally accepted.

The frequency diagrams described above provide useful background information for variation diagrams because they show the compositions of all

igneous rocks; one can tell at a glance whether a rock series is normal, abnormal, undersaturated, oversaturated, etc., and in what respect it differs from the average for 5000 analyses in Washington's Tables.[2]

Two areas have been selected as examples of the usefulness of the frequency diagrams and the differentiation index as a method of studying chemical variations in igneous rock series: (1) Highwood Mountains, Montana, alkaline province (Hurlbut, 1939; Larsen, 1941; Buie, 1941; and Burgess, 1941), and (2) Katmai, Alaska, petrographic province (Fenner, 1926) which is essentially "average" in composition. The weight per cent oxides of the rocks from these two areas are shown together as a function of differentiation index on figures 18a and 18b. Starting with the K_2O diagram, it can be seen that these two areas differ markedly. The Katmai volcanics fall slightly below the maximum for all rocks, whereas the Highwood analyses fall completely above the maximum and can be considered to be unusual in this respect.

The soda content of the Katmai rocks fall exactly along the maximum for all rocks and the Highwood rocks are low in soda at the mafic end and somewhat high at the salic end of the diagram. Perhaps this cross-over from low soda in the basalts to high soda in the salic volcanics is characteristic of alkaline petrographic areas.

The lime content of the Katmai rocks is again essentially "normal" in that it falls along the maximum for all rocks. Here again the Highwood area is unusual with a somewhat higher lime content than the average. The magnesia content of the Katmai rocks falls along the maximum and can be considered to represent an "average" distribution. The Highwood rocks are again quite different in that they carry considerably more magnesia than is average. The FeO and Fe_2O_3 content of the two series is essentially "normal". The relatively large "spread" of the analyses is probably related to analytical errors and slight oxidation of some specimens, for the abnormally high FeO values are usually related to a low Fe_2O_3 and vice versa.

Alumina in the Katmai rocks is normal in that the values are distributed along and just below the maximum for all rocks. In contrast, the alkaline Highwood series begins with low alumina at the basaltic end of the series, crosses the contour maximum and the trend of the Katmai series at approximately D.I. = 60, and continues on to unusually high alumina in the salic members of the series. This contrast in behavior of the Al_2O_3 curves is apparently a characteristic difference between oversaturated rocks series and undersaturated rock series.

The silica diagram again illustrates that the Katmai region is more or less average while the Highwood area is unusual. The silica values for the Katmai rocks trend along the contour maximum at slightly high silica values while the Highwood rocks fall well below the most populated area of the diagram.

In summary, the Highwood undersaturated rocks have oxide distributions that are unusual for all oxides except iron, while the oxide distributions of the Katmai rocks are essentially normal.

[2]Copies of these contoured diagrams can be obtained in reasonable numbers from the authors. They are printed on translucent paper with one percent equal to 2 mm on the D. I. coordinate, and one oxide percent equal to 4 mm on the oxide coordinate so that rock compositions can be plotted on them by superimposing on mm cross-section paper.

Classification of igneous rocks.—As the differentiation index is a measure of the amount of salic and femic constituents in the norm, it can be used as a classification of the igneous rocks. There is only one D.I. for each chemical composition and, when used in *connection with a modal classification*, it provides information on the basicity of a rock which the modal analysis alone does not supply. Each of the various rock types in a classification by modal composition has a wide range in chemical composition because of the extensive solid solution possible in the minerals as well as the range permitted by variations in the amounts of minerals present; the use of the D.I. *in addition* to the modal classification gives the petrologist some knowledge as to where a given rock falls in the range of admissible compositions. It is possible, for example, to have a granodiorite, an adamellite, and a granite all with the same chemical composition, the mineralogical difference being the result of the variable amount of plagioclase held in solid solution in the potassium feldspar. The D.I. of these three rocks would, of course, be the same and would indicate that they were chemically intermediate between a normal granite and a normal granodiorite.

Discussion.—The importance of the concept that the system SiO_2–$NaAlSiO_4$–$KAlSiO_4$ represents the goal of fractional crystallization of magmas and therefore a goal toward which all magmas tend to reach, has been considered in view of recent experimental studies and found to rest on a firmer foundation than when originally proposed by Bowen.

These experimental results, together with new evidence from the rocks themselves, put this concept of Bowen in the category of a petrologic law rather than of a theory or hypothesis.

The position of the rock in the series basic → salic can be quantitatively determined from the norm by summing the salic or femic constituents after certain minor readjustments in the normative minerals. We have chosen the salic constituents to calculate the differentiation index. Slight adjustments in the normative constituents of the salic and femic divisions are necessary because certain constituents such as anorthite of the salic group do not fall in petrogeny's residua system. It is certain, however, that the authors of the C.I.P.W. classification would have placed anorthite in the femic group had they had the benefit of experimental studies which were just beginning when the classification was formulated in 1902.

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