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CHEMICAL ANALYSES OF IGNEOUS ROCKS

PUBLISHED FROM 1884 TO 1913, INCLUSIVE

WITH A

CRITICAL DISCUSSION OF THE CHARACTER
AND USE OF ANALYSES

A REVISION AND EXPANSION OF PROFESSIONAL PAPER 14

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APPENDIX 3.

CALCULATION OF THE NORM.

INTRODUCTION.

Inasmuch as the exposition of the calculation of the norm in the quantitative system of classification and the tables of molecular numbers and percentage weights as originally published¹ may not now be readily accessible to all who use this collection of analyses, it has been thought that it would be useful to furnish these data in this volume.² The republication of this matter is the more advisable because the original statement of the calculation is very concise and because some changes have been suggested since the matter was first published.³ A very clear and detailed statement of the methods of calculation, illustrated by many examples and accompanied by the numerical tables, has lately been published by Finlay.⁴

In the present work considerable change has been made in the presentation of the calculation, though without altering its general principles, and the tables have been to some extent rearranged so as to make them more convenient for the ready calculation of the norms of the great majority of rocks. Some sections have been expanded and some contracted, as dictated by much experience, and a few errors have been corrected.

In the calculation of the norms of thousands of analyses I have found that the formal way of setting down the data in columns, as proposed in the original publication, followed by Finlay and generally used, involves some needless repetition and waste of time. Thus in calculating the feldspars and lenads there is no need of repeating for Al_2O_3 the figures for K_2O , Na_2O , and CaO ; or in calculating magnetite of setting down the figures for FeO and Fe_2O_3 , as they are necessarily identical. After several trials I have adopted and used for some years the arrangement shown in figure 1 (p. 37). By adopting such an arrangement, not putting down more figures than are necessary, and with a little practice and experience, it will be found

that the calculation of a norm takes but little time. For most rocks five minutes should suffice, but when readjustments have to be made (as because of deficiency in silica) the calculation may take ten minutes, or fifteen at the outside, in the most complicated norms.

The term *molecular number*⁵ is adopted here, instead of the commonly and previously used *molecular ratio*, *molecular proportion*, or the term *mol number*, suggested by Wright and Van Orstrand,⁶ because of the following considerations: The word *number* is preferable to *ratio* or *proportion* because the result obtained by dividing the weight percentage of any given constituent by its molecular weight is a number which is independent and irrespective of the other results similarly obtained. Thus, the result is not a ratio or proportion between such numbers. For rock analyses the term molecular is preferable to mol, as the quantities involved are molecules and are not related to any system of weights such as the definition of the term mol implies.

It is premised that in calculating the norm certain considerations should be borne in mind. The norm is the expression of the chemical composition of the rock in terms of standard mineral molecules, a list of which is given on page 1163. Some of the constituents enter only into "fixed" molecules, which are so called because they are incapable of change, whatever be the general chemical character of the rock. Thus ZrO_2 enters only into zircon (Z) as a standard mineral, P_2O_5 into apatite (ap), Cl into halite (hl), and so on. Other constituents may enter different mineral molecules according to the amounts of other constituents in the rock. Thus K_2O may enter orthoclase, leucite or kaliophilite; and Na_2O into albite or nephelite, according to the amount of available SiO_2 .

As regards Al_2O_3 , except when it is in excess of the sum of the alkalis and lime (the excess forming the corundum molecule), it is invariably present in the ratio of 1: 1 with K_2O , Na_2O , or CaO in the silic minerals orthoclase, leucite, kaliophilite, albite, nephelite, and anorthite. Consequently, where molecules of these minerals are considered in the following pages

¹ Cross, Whitman, Iddings, J. P., Pirsson, L. V., Washington, H. S., The quantitative classification of igneous rocks, pp. 186-203, 236-259, 1903.

² This republication has been suggested by a number of petrographers, among them Prof. A. Laeroix, of Paris, and Prof. A. Johannsen, of Chicago.

³ Cross, Whitman; Iddings, J. P., Pirsson, L. V., Washington, H. S., Jour. Geology, vol. 20, p. 557, 1912; Washington, H. S., Wash. Acad. Sci. Jour., vol. 5, p. 345, 1915.

⁴ Finlay, G. I., Introduction to the study of igneous rocks, New York, 1913.

⁵ This term is used also by Finlay.

⁶ Wright and Van Orstrand, Wash. Acad. Sci. Jour., vol. 3, p. 223, 1913.

any mention of K_2O , Na_2O , or CaO implies the consideration of an equal molecular amount of Al_2O_3 . Stress must also be laid on the fact that only the CaO which with an equal amount of Al_2O_3 enters anorthite is salic. The excess of CaO over this is femic.

The adjustment of the SiO_2 is one of the most important features in the calculation of the norm. The general principle followed involves a recognition of the so-called affinity of the different bases for SiO_2 and of the relative proportions of SiO_2 to base which each base can bind.¹ The order of affinity for SiO_2 , by which the distribution of this constituent is determined in calculating the norm, is as follows:



It should be noted that this order is not arbitrarily chosen but is founded on experience in petrography and mineralogy, supported by laboratory experiment, and that it accords in general with the occurrence of minerals in igneous rocks.

Stress must also be laid on the fact that the so-called standard minerals are understood to be *molecules* and not actual minerals. The misappreciation of this point has apparently led to some confusion of mind in regard to the norm.

NORMATIVE MINERAL MOLECULES.

	<i>Salic group.</i>	
Quartz (Q).....		SiO_2 .
Corundum (C).....		Al_2O_3 .
Zircon (Z).....		$ZrO_2 \cdot SiO_2$.
Orthoclase (or).....		$K_2O \cdot Al_2O_3 \cdot 6SiO_2$.
Albite (ab).....		$Na_2O \cdot Al_2O_3 \cdot 6SiO_2$.
Anorthite (an).....		$CaO \cdot Al_2O_3 \cdot 2SiO_2$.
Leucite (lc).....		$K_2O \cdot Al_2O_3 \cdot 4SiO_2$.
Nephelite (ne).....		$Na_2O \cdot Al_2O_3 \cdot 2SiO_2$.
Kaliophilite (kp).....		$K_2O \cdot Al_2O_3 \cdot 2SiO_2$.
Halite (hl).....		$NaCl$.
Thénardite (th).....		$Na_2O \cdot SO_3$.
Sodium carbonate (nc).....		$Na_2O \cdot CO_3$.
	<i>Femic group.</i>	
Acmite (ac).....		$Na_2O \cdot Fe_2O_3 \cdot 4SiO_2$.
Sodium metasilicate (ns).....		$Na_2O \cdot SiO_2$.
Potassium metasilicate (ks).....		$K_2O \cdot SiO_2$.
Diopside (di).....		$CaO(Mg,Fe)O \cdot 2SiO_2$.
Wollastonite (wo).....		$CaO \cdot SiO_2$.
Hypersthene (hy).....		$(Mg,Fe)O \cdot SiO_2$.
Olivine (ol).....		$2(Mg,Fe)O \cdot SiO_2$.
Calcium orthosilicate (cs).....		$2CaO \cdot SiO_2$.
Magnetite (mt).....		$FeO \cdot Fe_2O_3$.
Chromite (cm).....		$FeO \cdot Cr_2O_3$.
Ilmenite (il).....		$FeO \cdot TiO_2$.
Hematite (hm).....		Fe_2O_3 .
Titanite (tn).....		$CaO \cdot TiO_2 \cdot SiO_2$.
Perovskite (pf).....		$CaO \cdot TiO_2$.
Rutile (ru).....		TiO_2 .
Apatite (ap).....		$3(CaO \cdot P_2O_5) \cdot CaF_2$.
Fluorite.....		CaF_2 .
Pyrite (pr).....		FeS_2 .
Calcite (cc).....		$CaO \cdot CO_2$.

¹ Cf. Cross, Whitman, Iddings, J. P., Pirsson, L. V., Washington, H. S., The quantitative classification of igneous rocks, p. 191. Whether the order of this affinity is determined by something analogous to "chemical affinity" or is due to differences in solubility need not be discussed here. A general discussion of this subject and of the norm will form the subject of a separate paper.

Of these molecules quartz, corundum, sodium and potassium metasilicates, hematite, and rutile are what may be called "excess" molecules, as each represents an excess of some constituent over the amount which may be used to form other constituents.

THE CALCULATION.

The following statement of the rules for calculating the norm is based on the original presentation, but is modified in substance to accord with certain suggested minor changes and is modified in form so far as to represent the procedure adopted by me in calculating the norms found in Part I of the tables. In the description the word "amount" should always be understood to mean the molecular amount or the molecular number obtained by dividing the percentage weight of the constituent by its molecular weight.

1. The molecular number (amount) of each constituent is determined by reference to the table of molecular numbers, given on pages 1166-1170. If the result is less than 0.002 it may be neglected.

2. The amounts of MnO and NiO are to be added to that of FeO , and those of BaO and SrO to that of CaO .

The minor fixed molecules are first to be disposed of. The order in which this is done (3a-3i) is generally immaterial.

3a. An amount of CaO equal to 3.33 that of the P_2O_5 is allotted for apatite.

3b. An amount of Na_2O equal to that of the Cl_2 is allotted for halite.

3c. An amount of Na_2O equal to that of the SO_3 is allotted for thenardite. It must be remembered here that the SO_3 stated in the analysis often really represents the S of pyrite, so that rule 3c is applicable only when the rock contains minerals of the hauyne group.

3d. An amount of FeO equal to half that of S (or the S of erroneously stated SO_3 as above) is allotted for pyrite.

3e. An amount of FeO equal to that of the Cr_2O_3 is allotted for chromite.

3f. An amount of FeO equal to that of the TiO_2 is allotted for ilmenite. If there is an excess of TiO_2 an equal amount of CaO is to be allotted to it for provisional titanite, but only after the allotment of CaO to Al_2O_3 for anorthite (Rule 4d). If there is still an excess of TiO_2 it is calculated as rutile.

3g. An amount of CaO equal to half that of the F in excess of what is needed for apatite (that is, the 0.33 of CaO of 3a) is allotted for fluorite.

3h. If the rock is not decomposed and contains cancrinite, an amount of Na_2O equal to that of the CO_2 is allotted for sodium carbonate, which is to be considered as salic.¹ If the rock contains calcite, an amount of CaO equal to that of the CO_2 is allotted for calcite. If the modal calcite is primary, this normative calcite molecule is to be regarded as femic;

¹ This is a recent modification, see p. 31.

if the modal calcite is secondary or due to the assimilation of limestone, the calculated calcite molecule is to be disregarded as not forming part of the norm.

3i. An amount of SiO_2 equal to that of the ZrO_2 is allotted for zircon.

Of the allotments under Rule 3, only a and f are generally and b, c, and i occasionally necessary; the others are rarely called for.

4a. An amount of Al_2O_3 equal to that of the K_2O is allotted for provisional orthoclase.

4b. If there is an excess of K_2O over Al_2O_3 (an excess extremely rare), it is calculated as potassium metasilicate. For the Na_2O see Rules 5a and 5b.

4c. An excess of Al_2O_3 over the K_2O is allotted to an equal amount of remaining Na_2O for provisional albite. If there is insufficient Al_2O_3 , see Rule 4g.

4d. If there is an excess of Al_2O_3 over the $\text{K}_2\text{O} + \text{Na}_2\text{O}$ it is allotted to an equal amount of remaining CaO for anorthite.

4e. If there is an excess of Al_2O_3 over this CaO it is calculated as corundum.

4f. If there is an excess of CaO over this Al_2O_3 of 4d it is feric and reserved for diopside and wollastonite. (See Rules 7a and 7b.)

4g. If in 4c there is an excess of Na_2O over Al_2O_3 it is to be reserved for acmite and possibly for sodium metasilicate. (See Rules 5a and 5b.) There is then no anorthite in the norm.

5a. An amount of Fe_2O_3 equal to that of the excess of Na_2O over Al_2O_3 (see Rule 4g) is allotted to acmite.

5b. If there is still an excess of Na_2O over Fe_2O_3 (a rare excess) it is calculated as sodium metasilicate.

5c. If, as usually happens, there is an excess of Fe_2O_3 over Na_2O it is assigned to magnetite, an equal amount of FeO being allotted to it out of what remains from the formation of pyrite, chromite, and ilmenite. (See Rules 3d, 3e, 3f.)

5d. If there is still an excess of Fe_2O_3 it is calculated as hematite.

6. All the MgO and the FeO remaining from the previous allotments (see Rules 3d, 3e, 3f, and 5c) are added together and their relative proportions are ascertained (most easily by the use of a slide rule).

7a. To the amount of CaO from 4d is allotted provisionally an equal amount of $\text{MgO} + \text{FeO}$ to form diopside, the relative proportions of these two being preserved.

7b. If there is an excess of CaO it is reserved for provisional wollastonite.

7c. If there is an excess of $\text{MgO} + \text{FeO}$ over that needed for diopside (7a) it is reserved for provisional hypersthene.

All the oxides except SiO_2 have now been assigned to actual or provisional mineral molecules and we have next to consider the distribution of the silica.

8a. The sum of the amounts of silica needed to form zircon from ZrO_2 (Rule 3i, 1:1), titanite from CaO

(Rule 3f, 1:1), acmite from excess Na_2O (Rule 5a, 4:1), potassium and sodium metasilicates from excess K_2O and Na_2O (Rules 4b, 5b, 1:1), and *provisional* orthoclase from K_2O (Rule 4a, 6:1), albite from Na_2O (Rule 4c, 6:1), anorthite from CaO (Rule 4d, 2:1), diopside from $\text{CaO} + (\text{Mg}, \text{Fe})\text{O}$ (Rule 7a, 1:1), wollastonite from excess CaO (Rule 7b, 1:1), and hypersthene from $(\text{Mg}, \text{Fe})\text{O}$ (Rule 7c, 1:1) is subtracted from the total SiO_2 .

8b. If there is an excess of SiO_2 , as there commonly is, it is calculated as quartz.

8c. If there is a deficiency of silica in 8a the SiO_2 allotted to hypersthene (Rule 7c) is subtracted from the general sum of 8a and the remainder subtracted from the total SiO_2 . If there is here an excess of SiO_2 it is allotted to the $(\text{Mg}, \text{Fe})\text{O}$ of 7c to form hypersthene and olivine, and is distributed according to equations (1) and (2):

Let x = the number of hypersthene molecules and y = the number of olivine molecules, then—

$$(1) \quad x + y = \text{the amount of available } (\text{Mg}, \text{Fe})\text{O and}$$

$$(2) \quad x + \frac{y}{2} = \text{the amount of available } \text{SiO}_2.$$

In this operation the relative proportion of MgO and FeO determined in 6 and used in forming diopside (Rule 7a) is to be preserved. The fixed and provisional molecules of Rule 8a are calculated into their percentage weights. If there is not enough silica to equal half the amount of $(\text{Mg}, \text{Fe})\text{O}$ of Rule 7c, all the $(\text{Mg}, \text{Fe})\text{O}$ of Rule 7c is calculated as olivine, SiO_2 equal to half its amount being assigned to it.

8d. If there is a deficiency of SiO_2 in 8c, the SiO_2 allotted to titanite (3f) is subtracted from the general sum of 8a, and the $\text{CaO} + \text{TiO}_2$ calculated as perovskite.

To follow strictly the order of affinity for SiO_2 stated on page 1163 we should now distribute SiO_2 between wollastonite and calcium orthosilicate, but as calcium orthosilicate is represented modally—that is, among actual minerals—in igneous rocks only in the very rare melilite, which also always occurs in rocks containing little SiO_2 and abundant nephelite, little albite, and often considerable leucite, we next take up the distribution of SiO_2 between albite and nephelite as representing most closely the facts of actual mineral occurrence.

8e. The sum of the SiO_2 needed to form the molecules of 8a is deducted from the total SiO_2 , except that olivine is substituted for hypersthene, and perovskite for titanite, and that albite is not included. If there is an excess of more than twice (and, of course, less than six times) that of the Na_2O for the provisional albite of 8a this is distributed between albite and nephelite according to equations (3) and (4):

Let x = the number of albite molecules and y = the number of nephelite molecules, then—

$$(3) \quad x + y = \text{the amount of available } \text{Na}_2\text{O, and}$$

$$(4) \quad 6x + 2y = \text{the amount of available } \text{SiO}_2.$$

8f. If there is still a deficiency of SiO_2 —that is, in 8e, not enough to equal twice the amount of available Na_2O —all this Na_2O is allotted to nephelite and the K_2O is distributed between orthoclase and leucite, as follows: The sum of the SiO_2 needed for the molecules in 8a is subtracted from the total SiO_2 , olivine being substituted for hypersthene, perovskite for titanite, and nephelite for albite, and orthoclase being disregarded. If there is an excess of more than four times (and, of course, less than six times) that of K_2O it is distributed between orthoclase and leucite according to equations (5) and (6):

Let x = the number of orthoclase molecules and y = the number of leucite molecules, then—

$$(5) \quad x + y = \text{the amount of available } \text{K}_2\text{O, and}$$

$$(6) \quad 6x + 4y = \text{the amount of available } \text{SiO}_2.$$

8g. If there is still a deficiency of SiO_2 —that is, in 8f not enough to equal four times the amount of K_2O —we have to distribute the CaO of wollastonite and diopside between these two and calcium orthosilicate, and the $(\text{Mg}, \text{Fe})\text{O}$ of diopside between diopside and olivine, according to the available SiO_2 . This distribution is made as shown below.¹ There are two possible cases; either there is sufficient wollastonite to reduce to orthosilicate or there is not.

The most frequent case is that in which there is no wollastonite or its amount is insufficient to satisfy the deficiency in SiO_2 . Here, after allotting SiO_2 to form leucite, nephelite, anorthite, acmite, olivine of rule 8c, and possibly zircon and sodium metasilicate, the amount thus used is deducted from the total SiO_2 , the residue being the "available silica." Letting d = the number of new diopside molecules, f = the number of new olivine molecules, and c = the number of calcium orthosilicate molecules, we have the equations—

$$(7) \quad 2d + f + c = \text{the amount of available } \text{SiO}_2.$$

$$(8) \quad d + 2f = \text{the amount of } (\text{Mg}, \text{Fe})\text{O (of provisional diopside)}.$$

$$(9) \quad d + 2c = \text{the amount of } \text{CaO} \text{ of provisional diopside and wollastonite.}$$

These equations can be solved, of course, in several ways, but that which I have adopted is as follows: Subtracting (7) from the sum of (8) and (9) we get the value of $f + c$; substituting this in (7) d is found, and then from (8) and (9) f and c are found successively.

In the second case, where there is sufficient tentative wollastonite to meet the deficiency of SiO_2 , the total amount of SiO_2 in the rock is subtracted from the sum of the SiO_2 which has been allotted to leucite, nephelite, anorthite, acmite, diopside, olivine, and to tentative wollastonite. The deficit is the number of molecules of necessary calcium orthosilicate, and also the amount of SiO_2 to be assigned to it. This requires twice as much CaO . The rest of the CaO remains in wollastonite and takes an equal amount of SiO_2 , while the diopside remains unchanged.

8h. If, as may very rarely happen, there is not even enough SiO_2 to form leucite, we must assume the presence of the kaliophilite molecule in the norm and distribute the K_2O between this and leucite. For this the sum of the SiO_2 needed for nephelite, anorthite, acmite, sodium metasilicate, olivine, calcium orthosilicate, and zircon is subtracted from the total SiO_2 , and the amounts of leucite and kaliophilite are calculated according to the following equations (10) and (11):

Let x = the number of leucite molecules and y = the number of kaliophilite molecules, then—

$$(10) \quad x + y = \text{the amount of } \text{K}_2\text{O, and}$$

$$(11) \quad 4x + 2y = \text{the amount of available } \text{SiO}_2.$$

9. Having thus adjusted the amounts of the SiO_2 , and all the other constituents between the fixed molecules and those with differing ratios of SiO_2 (the provisional becoming actual molecules), they are calculated into the percentage weights of the mineral molecules of the norm by the use of the tables on pages 1172–1180.

¹ Washington, H. S., Wash. Acad. Sci. Jour., vol. 5, p. 346, 1915.