NIGGLI'S PRINCIPLES OF IGNEOUS PETROGENESIS

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RECENT advances in igneous petrogenesis are based almost entirely on the researches made at the Geophysical Laboratory, Washington. The phase relationships of various systems that are studied with improved modern technique, have given valuable insight into the possible mode of origin of rock-forming minerals from silicate melts. Valuable though such knowledge is, there remains the fact that the fundamental cause may have to be sought for in a sphere that defies experimental analysis. After all experiments are directed to determine the physical and chemical conditions that control the formation of minerals. But the genesis of minerals and their pattern are the natural outcome of a directed dynamic force.

In the organic world, a plant has its identity determined by the seed, and an animal by the egg. It would be difficult to decide how far external influences have their effects on the embryo and in what manner. Though how a seed gives rise to a particular plant and an egg to a particular animal is known, why they should do so is beyond scientific comprehension. A mineral too has its pattern determined by forces at work in the melt state.

Hence our solved problems in the laboratories are not to be considered as ends in themselves. There remain undoubtedly problems, the solutions of which are to be found only in the realm of speculation.

Niggli considers that petrogenetic causes are to be traced to reactions that take place in the melt, in other words, homogeneous equilibria conditions.

The study of petrogenetic and allied problems is usually based on the weight percentages of oxides taken as units. According to Niggli, such units cannot be anything more than the raw material which require scientific and critical treatment to discover hidden values. x grams of MgO do not correspond to x grams of Na_2O or Al_2O_3. Therefore " to combine x grams of K_2O and y grams of Na_2O to form z grams of alkali oxides, is just as meaningless as adding x grams of apples to y grams of potatoes ".

He therefore advocates that atomic and molecular values derived from the weight percentages of oxides, form the units for petrogenetic studies.

They give a correct picture of the fundamental chemical characteristic of the mineral or the rock, as a whole. They are valuable in interpreting the mode of origin of minerals, in making comparative studies of minerals and in the classification of rocks. They have the sanction of studies based on atomic chemistry.

CLASSIFICATION OF IGNEOUS ROCKS

Niggli Values.—For purposes of classification, Niggli has taken primarily into consideration:

(1) alumina,
(2) oxides of iron and magnesium,
(3) lime, and
(4) alkalies.

These four items are represented by symbols which together with the mode of calculation are given below:

(1) Determine the molecular numbers,

$$\text{Molecular numbers} = \frac{\text{weight percentage}}{\text{molecular weight}} \times 1{,}000.$$

(2) Add the molecular numbers of:

		Molecular numbers	Niggli symbols
(*a*) Al_2O_3, Cr_2O_3 and rare earths	..	m'	al
(*b*) $Fe_2O_3 \times 2$, FeO, MgO and MnO	..	n'	fm
(*c*) CaO, SrO and BaO ..	..	p'	c
(*d*) Na_2O, K_2O and Li_2O ..	..	q'	alk

The total molecular numbers of

al, fm, c and alk $= (m' + n' + p' + q') = x'$ (say)

The percentages are then determined thus:

$$\text{al} = \frac{m'}{x'} \times 100$$

$$\text{fm} = \frac{n'}{x'} \times 100$$

$$\text{c} = \frac{p'}{x'} \times 100$$

$$\text{alk} = \frac{q'}{x'} \times 100$$

In addition to these four values, other Niggli values are derived thus:

$$\text{Stated on per cent. basis}\left\{\begin{array}{l} \mathrm{si} = \dfrac{\text{mol. no. of } SiO_2}{x'} \times 100 \\[2ex] \mathrm{ti} = \dfrac{\text{mol. no. of } TiO_2}{x'} \times 100 \\[2ex] \mathrm{p} = \dfrac{\text{mol. no. of } P_2O_5}{x'} \times 100 \end{array}\right.$$

$$\text{Stated as a ratio}\left\{\begin{array}{l} \mathrm{k} = \dfrac{\text{mol. no. of } K_2O}{\mathrm{alk}} \\[2ex] \mathrm{mg} = \dfrac{\text{mol. no. of MgO}}{\mathrm{fm}} \end{array}\right.$$

Thus the molecular values—al, fm, c, alk, si, ti, and p are expressed on a percentage basis, whereas k and mg are expressed as a ratio.

qz, a derived value, known as quartz index is also used.

$$\mathrm{qz} = \mathrm{si} - \mathrm{si}', \text{ where } \mathrm{si}' = 100 + 4\,\mathrm{alk}, \text{ when } \mathrm{alk} < \mathrm{al}.$$

$$\mathrm{qz} = \mathrm{si} - (100 + 3\,\mathrm{al} + 1\,\mathrm{alk}) \text{ when } \mathrm{alk} > \mathrm{al}.$$

qz may be positive or negative and gives valuable clue of the minerals expected to be formed.

On the basis of these values the eruptive rocks are classified into calc-alkali, soda-rich and potash-rich divisions. The divisions are subdivided into groups and magma types as mentioned below:

Calc-alkali division, into 13 groups with a total of 64 types.

Soda-rich division, into 15 groups with a total of 65 types.

Potash-rich division, into 12 groups with a total of 45 types.

One example of the calc-alkali division with the types is given below:

TABLE I

Division:
Calc-alkali

Group:
Hornblendite magma

Types	si	al	fm	c	alk	k	mg
1. al-hornblendite ..	.. 120	19	61	15	5	..	0·7
2. hornblendite ..	.. 80	15	60	20	5	..	0·6
3. hornblende peridotite	.. 80	10	74	14	2	..	0·7
4. diallagite ..	.. 90	7	68	23	2	..	0·7
5. websterite ..	.. 95	1	80	18	1	..	0·8

Generally alk $\leqq$ 8
al $\leqq$ 18·5
fm $>$ 50
c — 9 to 26

1.	si range ..	135—70	al about 20	c<23	
2.	si ..	135—65	al≧10	c—15 to 26	fm<70
3.	si ..	120—50	al about 12 to 7·5	c— 9 to 20	fm≧70/69
4.	si ..	120—65	al<10	c≧20	fm nearly 70, alk practically nil
5.	si	120—55	al<7·5	c— 9 to 22	fm≧70, alk practically nil

TABLE II

Molecular numbers and Atom numbers

Hornblende Norite—St. Thomas Mount, Madras

Constituents	p.c.	Mol. No.×1,000	Atom No.
SiO_2	50·04	834	834
Al_2O_3	11·65	114·5	229
Fe_2O_3	2·63	16·4	33
FeO	15·76	218·5	218·5
MnO	..	..	..
MgO	5·58	139·5	139·5
CaO	7·89	141	141
Na_2O	3·08	50	100
K_2O	0·89	10	20
TiO_2	1·93	24	24
P_2O_5	0·20	1·0	2
H_2O+	0·19	..	..
Total	99·84		

Analyst—Washington

TABLE III

Calculation of Niggli Values

Niggli symbols		Molecular numbers		Niggli values
al	$Al_2O_3 + Cr_2O_3 +$ Rare Earths .. $114{\cdot}5 + 0 + 0$	115	$\frac{115}{707} \times 100$	16·27
fm	$FeO + Fe_2O_3 + MgO + MnO$ $218{\cdot}5 + 33 + 139{\cdot}5 + 0$	391	$\frac{391}{707} \times 100$	55·30
c	$CaO + BaO + SrO$ .. .. $141 + 0 + 0$ ..	141	$\frac{141}{707} \times 100$	19·95
alk	$K_2O + Na_2O + Li_2O$ .. .. $10 + 50 + 0$ ..	60	$\frac{60}{707} \times 100$	8·48
		707		100·00
si	.. ..	834	$\frac{834}{707} \times 100$	118·00
ti	.. ..	24	$\frac{24}{707} \times 100$	3·404
k	$\frac{K_2O}{K_2O+Na_2O}$	..	$\frac{10}{60}$	0·166
Mg	$\frac{MgO}{fm}$	..	$\frac{139{\cdot}5}{391}$	0·357

If the rock is an eruptive one it belongs to

Group	..	Hornblendite Magma	Refer values already given.
Type	..	'Hornblendite'	

If it is metamorphic it must have been derived from a calc-alumino-silicate rock with appreciable quantities of alkalies, say an alkali calc shale.

CHEMICAL EQUILIBRIUM IN MAGMATIC MELTS

Matter is said to be in equilibrium with its surroundings if it does not show any tendency to change. This condition of equilibrium is defined as a "system". A system exists as such so long as the physical and chemical conditions remain unaltered. Such equilibrium conditions may be obtained in homogeneous and heterogeneous bodies. In a homogeneous system every part of the system has absolutely the same physical and chemical properties as every other part. An unsaturated solution of sodium chloride or a silicate melt (magma) is an example of a homogeneous system.

Heterogeneous Equilibrium.—In over-saturated conditions sodium chloride settles down from the solution. There comes a bounding surface between the solid and the solution. The physical and chemical properties of the solid are different from those of the solution. The two together constitute a heterogeneous system. This system is in equilibrium so long as the physical and chemical conditions remain the same. In the same way the moment the first mineral crystallizes from a silicate melt a new solid phase sets in, by which is meant a physically homogeneous but mechanically separable portion of a system. Thus the homogeneous system is changed to a heterogeneous system.

The mineral that crystallizes reacts with the liquid in which it is immersed, continuously or discontinuously, giving rise to additional minerals making the system more and more complex.

A systematic study of the temperatures at which synthetic minerals are in equilibrium with silicate melts of known composition is one of the set programmes of the Geophysical Laboratory, Carnegie Institute of Washington. The petrologic bearing of these studies is made out by equilibrium diagrams according to phase rule methods. The experimental facts have greatly added to the knowledge of the physico-chemical conditions relating to crystal differentiation in binary, ternary and quarternary systems. Bowen's crystallization differentiation theory has been generally accepted by distinguished petrologists all the world over. But the fact remains that the "crucible" experiments indicate only the conditions under thermodynamic equilibrium and fail to take into account "the kinetics of the processes involved in fractional crystallization".

Niggli is an advocate of Bowen's differentiation theory. But he points out "while all knowledge in this respect is unquestionably of the utmost value, the fact may not be overlooked that there must exist laws of a higher order, which govern the entire complex of phenomena".

Homogeneous Equilibrium.—Niggli searches for the cause, in the reactions that take place among the molecules while in the fluid state. An insight into the laws that govern reactions in the melt state, *i.e.*, under homogeneous equilibria conditions, would enable one to forecast what "new phase must appear during crystallization, taking place under circumstances of any kind" —(Niggli). The birth of a mineral is determined by laws that operate in the pre-birth condition.

The laboratory experiments themselves are suggestive in this regard. The metasilicate clinoenstatite ($MgSiO_3$) melts incongruently into the orthosilicate Mg_2SiO_4 at 1,557° C. There is a theoretical possibility of its further dissociation into MgO and SiO_2. Does not this suggest that the orthosilicate has very little tendency to dissociate, and lead to the hypothesis of its independent existence in the "melt"? The polysilicate orthoclase ($KAlSi_3O_8$) melts incongruently into leucite ($KAlSi_2O_6$) at 1,170° C. A still lower silicated mineral ($KAlSiO_4$) has been observed to exist in the study of the system K_2O–Al_2O_3–SiO_2. Again the dissociation of mullite ($Al_6SI_2O_{13}$) into corundum (Al_2O_3) and liquid at 1,810° C. leads to the possibility of the existence of Al_2O_3 molecule in the melt. Hence can we not postulate the potential existence of K_4SiO_4 and Na_4SiO_4 in a melt, which on combining with Al_2O_3 give rise respectively to $KAlSiO_4$ and $NaAlSiO_4$?

The emphasis is on the fact that Mg_2SiO_4, $KAlSIO_4$ and other orthosilicates such as $NaAlSiO_4$ and Ca_2SiO_4 are unstable while SiO_2 molecules are present in the melt. It is even possible that molecules such as K_4SiO_4 and Na_4SiO_4 give rise to $KAlSiO_4$ and $NaAlSiO_4$ by reacting with Al_2O_3.

Basis Molecules.—The fundamental compounds that exist in the magma are called basis molecules. There is no reason to suppose that these could be present in larger amount in a further state of dissociation. These bases on further reaction are considered to have given rise to new minerals. At this stage the following questions arise:

(i) What are the characteristics of the basis molecules?

(ii) Are the reaction equations to be balanced by weight, or by volume?

Chemical reactions are based on the principle that each element has a definite combining weight or equivalent weight, and that the combinations occur in simple multiples of these quantities. The atomic weight is either identical with the combining weight or an integral multiple of it.

Atomic weight = Equivalent weight × Valency.

Hence the atomic weight is sometimes called the combining weight.

Volume Unit.—But in petrological studies the first feature that strikes one on examining a rock megascopically or microscopically is the fabric of the rock, restricting the term "fabric" to define the sum-total of the textural and structural features of the mineral constituents. Petrogenesis seeks to explain the factors that have led to the development and proportion of minerals, as we see them in the rock. For most petrological work, the planemetric analysis is resorted to in order to give the weight percentage of the oxides. In this analysis the volume percentage is obtained directly. Such being the case, it would be only appropriate to base reaction equations on a volume basis.

It is now an established fact that the electro-positive character of the elements is the root cause of the chemical reactions leading to mineral formation. The more electro-positive a metal is, the greater its affinity for a particular non-metal or a radical. The atomic number denotes the number of protons or of positive electricity in the nucleus of the atom. If two minerals A and B combine to form C, it may be considered as due to the atomic number of A having combined with that of B to give rise to that of C. C has an atomic number equal to the sum of the atomic numbers of A and B.

Atom Numbers as Units.—Instead of summing up the atomic numbers of the elements, there would be a justification in summing up the actual number of electro-positive atoms themselves, if the atomic numbers of the elements are the same. But they are not of course the same. However, for calculation purposes, we could consider them to be the same, and treat them all alike if the atomic numbers of the reacting elements do not vary much.

Thus the atomic number of magnesium is 12: that of silicon is 14.

$MgO + SiO_2$ .. .. .. $MgSiO_3$
$12 + 14$ 26

Or

$1 + \frac{14}{12}$ .. .. .. $\frac{26}{12}$

If the difference $\frac{1}{6}$ is neglected, then

$MgO + SiO_2$ .. .. .. $MgSiO_3$
$1 + 1$ 2

It is interesting to note that the atomic numbers of the elements that enter into *the composition of* the rock-forming minerals show a range of 11 to 26 only as seen below:

Element	Atomic No.
Si	14
Al	13
Fe	26
Mg	12
Mn	25
Ca	20
Na	11
K	19

This range may be ignored as the actual variation in atomic numbers in all the elements taken together is 1 to 92.

Mineral Formula.—As the sum of the electro-positive elements in a molecule will give a number which denotes the maximum capacity of the molecule for reaction, it should be possible to state the formula of a mineral in a form, which besides indicating its chemical constitution would also connote its capacity for reaction.

Let us take an example. Forsterite has the composition 2 $MgOSiO_2$. Its chemical constituents are Mg, Si and O. The number of electropositive atoms are 3 (2 of Mg and 1 of Si).

(By definition, a basis molecule has only 1 electro-positive charge. Hence the basis molecule forsterite is $\frac{1}{3}$ Mg_2SiO_4; it is given the symbol Fo.)

Thus the following table gives examples of the formulæ and symbols of a few basis molecules.

TABLE IV

Some Mineral Molecules

Mineral molecule	No. of electro-positive atoms (Cations)	Basis (Equivalent formula unit)	Symbol
Mg_2SiO_4	Mg + Si = 3 2 + 1	$\frac{1}{3}$ Mg_2SiO_4	Fo
$KAlSiO_4$	K + Al + Si = 3 1 + 1 + 1	$\frac{1}{3}$ $KAlSiO_4$	Kp
$NaAlSiO_4$	Na + Al + Si = 3 1 + 1 + 1	$\frac{1}{3}$ $NaAlSiO_4$	Ne
$CaAlAlO_4$	Ca + Al + Al = 3 1 + 1 + 1	$\frac{1}{3}$ $CaAlAlO_4$	Cal
SiO_2	Si = 1 1	SiO_2	Q

The formation of new minerals results thus:

(*a*) By reaction of a basis with another basis.
Example :

		Basis Kaliophyllite		Basis Quartz		Mineral Orthoclase
Symbol ..	..	Kp		Q		Or
Formula ..	..	$KAlSiO_4$	+	$2\ SiO_2$	=	$KAlSi_3O_8$
Niggli formula	..	3 Kp	+	2 Q	=	5 Or

(*b*) By reaction of a basis with a mineral.
Example :

		Basis Kaliophyllite		Mineral Orthoclase		Mineral Leucite
Symbol ..	..	Kp		Or		Lc
Formula ..	..	$KAlSiO_4$	+	$KAlSi_3O_8$	=	$K_2Al_2Si_4O_{12}$
Niggli formula	..	3 Kp	+	5 Or	=	8 Lc

(*c*) By reaction of a mineral with another mineral.
Example :

		Mineral Wollastonite		Mineral Enstatite		Mineral Diopside
Symbol ..	..	Wo		En		Di
Formula ..	..	$CaSiO_3$	+	$MgSiO_3$	=	$CaMgSi_2O_6$
Niggli formula	..	2 Wo	+	2 En	=	4 Di

The coefficients are obtained by summing up the electro-positive elements. Thus in the example (*b*):

$$
\begin{aligned}
3\ \mathrm{Kp} &= 1\ \mathrm{K} + 1\ \mathrm{Al} + 1\ \mathrm{Si} \\
5\ \mathrm{Or} &= 1\ \mathrm{K} + 1\ \mathrm{Al} + 3\ \mathrm{Si} \\
8\ \mathrm{Lc} &= 2\ \mathrm{K} + 2\ \mathrm{Al} + 4\ \mathrm{Si}
\end{aligned}
$$

It may also be pointed out that since

$$
\begin{aligned}
3\ \mathrm{Kp} + 2\ \mathrm{Q} &= 5\ \mathrm{Or} \\
30\ \mathrm{Kp} + 20\ \mathrm{Q} &= 50\ \mathrm{Or} \\
60\ \mathrm{Kp} + 40\ \mathrm{Q} &= 100\ \mathrm{Or}
\end{aligned}
$$

and similarly in other cases. For there is a proportionate increase in the number of electro-positive atoms.

In this mode of calculation, H, C, N, O and F—elements of the first horizontal series of the periodic table—are not counted. In sulphides and halides S and Cl are not counted, as they take the place of O. But these are counted as electro-positive in sulphates and chlorates, This principle has a great advantage in metamorphic processes. For, S, H_2O and CO_2 need not be considered, as the addition of any in a forward reaction is balanced by the escape of the same in the reverse reaction. Hence such constituents are put within brackets.

Examples.—(1) Muscovite and quartz, by metamorphism can change over to orthoclase, andalusite, and water. The reaction equations are:

$$\begin{array}{ccccccccc} \text{Muscovite} & + & \text{Quartz} & \rightarrow & \text{Orthoclase} & + & \text{Andalusite} & + & \text{Water} \\ KAl_3Si_3O_{10}(OH)_2 & + & SiO_2 & \rightarrow & KAlSi_3O_8 & + & Al_2SiO_5 & + & (H_2O) \\ 7\ Ms & + & 1\ Q & \rightarrow & 5\ Or & + & 3\ Sil & + & (W) \end{array}$$

(2) Cordierite, orthoclase and water can change over to biotite, muscovite and quartz. The reaction equations are:

$$\begin{array}{ccccc} \text{Cordierite} & & \text{Orthoclase} & & \text{Water} \\ 3\,(Mg, Fe)_2Al_4Si_5O_{18} & + & 8\ KAlSi_3O_8 & + & 8\ H_2O \\ 33\ Cord & + & 40\ Or & + & (8\ W) \end{array}$$

$$\begin{array}{cccccc} & \text{Biotite} & & \text{Muscovite} & & \text{Quartz} \\ \longrightarrow & 2\ K\,(Mg, Fe)_3AlSi_3O_{10}\,(OH)_2 & + & 6\ KAl_3Si_3O_{10}\,(OH)_2 & + & 15\ SiO_2 \\ & 16\ Bi & + & 42\ Ms & + & 15\ Q \end{array}$$

Summary.—To summarise, chemical reactions can be conceived to take place in the melt condition. The melt is postulated to contain low silicated molecules such as Mg_2SiO_4, $KAlSiO_4$, etc. These *plus* basis molecules, by reaction, give rise to simple mineral molecules. The latter may combine among themselves, or with the basis molecules and lead to the development of other minerals. Even the growth of complex minerals can be explained by such reactions.

The reaction equations are represented in a simple manner. As the electro-positive character of the elements is directly responsible for chemical reaction, the sum of the atomic numbers of the electro-positive atoms of the reactants and that of the resulting minerals could be balanced. But as there is scarcely any difference in the atomic numbers of the elements that go to build the rock-forming minerals, no great error comes in the equation if they are balanced by taking into account the sum of the electro-positive atoms on both sides of the equation.

The basis and the mineral molecules are given symbols. Thus Q stands for quartz. Or means orthoclase. Reaction equations are made with co-efficients that denote the number of the electro-positive atoms in the constituents.

Example :

$$10\,\mathrm{Or} + 12\,\mathrm{En} + (2\,\mathrm{W}) \rightarrow 16\,\mathrm{Bi} + 6\,\mathrm{Q}.$$

According to this line of thought the oxides which are more fundamental than even the basis molecules, from the reaction point of view, should have equivalent volumes.

The following table shows that the oxides satisfy nearly this condition.

TABLE V

Rock-Forming Oxides

	Equivalent weight	Equivalent volume
SiO_2	60·1	22·7
1/2 Al_2O_3	51·0	12·9
1/2 Fe_2O_3	79·8	15·1
FeO	71·8	11·8
MnO	70·9	13·2
MgO	40·3	11·3
CaO	56·1	16·7
1/2 Na_2O	31·0	12·8
1/2 K_2O	47·1	18·2
TiO_2	79·9	18·9

The following table gives a list of 'Basis Molecules' with their respective symbols.

TABLE VI

Basis Molecule Groups

	Basis (Equivalent formula unit)	Symbol	Equivalent weight		Basis (Equivalent formula unit)	Symbol	Equivalent weight
1/3	K Al Si O_4	Kp	52·7	1	Si O_2	Q	60·1
	Na Al Si O_4	Ne	47·4		Ti O_2	Ru	79·9
	Ca Al Al O_4	Cal	52·7		Fe S_2	Pr	120·0
	Mg Al Al O_4	Sp	47·4		Ca F_2	Fr	78·1
	Fe Al Al O_4	Hz	57·9	1/5	Ca_3 P_2O_8	Cp	62·1
	K K Si O_3	Ks	51·4	1	Ca CO_3	Cc	100·0
	Na Na Si O_3	Ns	40·7	1/2	CaS O_4	A	68·1
	Ca Ca Si O_4	Cs	57·4	1/3	Na_2S O_4	Th	47·3
	Mg Mg Si O_4	Fo	46·9	1/2	Na_2 CO_3	Nc	53·0
	Fe Fe Si O_4	Fa	67·9	1/3	Fe_2Si O_5	Fs	73·2
	Fe Cr Cr O_4	Cm	74·6		H_2O	W	0
1	Na Cl	Hl	116·9				
1/2	Al Al O_3	C	51·0				
	Fe Fe O_3	Hm	79·8				
	Zr Si O_4	Z	91·6				

It is best to remind ourselves that the aim of the study is to trace the line of development or growth of the rock as we have it for study.

This involves:

(1) The determination of the constituents either

(*a*) by the planemetric analysis and the calculation to percentage weight, knowing the specific gravity; or

(*b*) by actual chemical analysis.

(2) The compounding of the oxides to determine the basis.

(3) Compounding the basis to form the minerals *we see* which will be called katanorms.

(4) Recognising the possibility of different lines of comoination which would yield different katanorms.

(5) Finally synthesising them in such a way as to lead to the goal of modal percentage and drawing out inferences from the changes in the mineral constitution. That is, a suite of rocks may have a katanorm combination A and may also have another katanorm B or "katavariant". If two rocks in this suite have their modal percentage corresponding to A and B, a consanguinitic relationship of one to the other is established.

Or again, in a metamorphic suite, A, B and C may represent the kata-mezo and epizonal conditions.

Petrogenetic studies involve the searching for the cause of the katanormative variant corresponding to the modal mineral variant.

It should be obvious that Niggli's molecular norm—based on fundamental values, is adapted to bring out the relationship between chemical composition and mineral constituents of igneous and metamorphic rocks. The CIPW norm that is based on weight percentages of *hypothetical* normative minerals sometimes leads to the determination of norms not at all present in the mode. Tom F. W. Barth observes:

> "The calculation of the so-called 'norm' (CIPW norm) is a tool which, particularly for igneous rocks, has proved its great value. But in metamorphic rocks, in which the interrelation of mineralogy and chemistry is of the utmost importance, the norm classification has failed. The reason is obvious: The normalization of the different metamorphic mineral facies encounters great difficulties in a norm based on weight percentages. The chemical relations of a rock in terms of weight percentages obscure the comprehensive view; the computations, moreover, become unnecessarily cumbersome. I propose, therefore, that calculation of the classical weight norm be altogether

discontinued. I regard it as obsolete and superseded partly by the Niggli 'molecular norm', partly by the norm of the standard cell, as will be introduced in the present paper."

BASIS—RULES FOR THE CALCULATION

I. From Atom Numbers

1. Determine the molecular numbers of the constituent oxides

$$\text{Mol. No.} = \frac{\text{Weight percentage of the oxide}}{\text{Molecular weight}} \times 1{,}000.$$

2. Determine the number of atoms in each constituent from the molecular numbers as follows:

The number of atoms are obtained by multiplying the molecular numbers by 2 in the case of Al_2O_3, Fe_2O_3, Na_2O, K_2O and P_2O_5.

3. The number of atoms which may hereafter be called "atom numbers" are equal to the molecular numbers in the case of SiO_2, TiO_2, FeO, MnO, NiO, MgO, and CaO. This also holds good for H_2O.

4. The atom numbers of:

(*a*) MnO and NiO are added to FeO,
(*b*) SrO and BaO to CaO,
(*c*) Li_2O to K_2O,
(*d*) Cr_2O_3 to Al_2O_3.

5. Appreciable quantities of P_2O_5, Cl, F and S are directly converted into basis molecules.

P_2O_5 will form the basis apatite .. (Cp)
Cl will form the basis halite .. (Hl)
F will form the basis fluorite .. (Fr)
S will form the basis pyrite .. (Pr)

6. Very small quantities of the constituents can be ignored.

7. The number of atoms in each constituent is always referred to with a symbol, the first letter being in capitals thus:

(*Symbols of Atom Numbers*)

Constituents ..	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2
Symbol ..	Si	Al	Fe'''	Fe''	Mg	Ca	Na	K	Ti

Procedure

A

K

(i) Start with K and allot equivalent quantity of Al and S to make Kp which has the formula 1/3 KAl SiO_4. Thus,

$$x\mathrm{K} + x\mathrm{Al} + x\mathrm{Si} = 3x\mathrm{Kp} = 3x\left[\frac{\mathrm{KAl\ SiO_4}}{3}\right]$$

(ii) If K > Al, the balance of K after (i) is converted into the basis 1/3 K_2SiO_3 = Ks, thus,

$$y\mathrm{K} + \frac{y}{2}\,\mathrm{Si} = \frac{3}{2}\,y\mathrm{Ks} = \frac{3}{2}\,y\left[\frac{\mathrm{K_2SiO_3}}{3}\right]$$

(iii) If Al remains after the saturation of K, then proceed with the calculation of basis Ne with Na.

B

Na

(i) $$x\mathrm{Na} + x\mathrm{Al} + x\mathrm{Si} = 3x\mathrm{Ne} = 3x\left[\frac{\mathrm{Na\ Al\ SiO_4}}{3}\right].$$

(ii) If Na is in excess of Al, the balance of Na is converted into the basis Ns.

$$y\mathrm{Na} + \frac{y}{2}\,\mathrm{Si} = \frac{3}{2}\,y\mathrm{Ns} = \frac{3}{2}\,y\left[\frac{\mathrm{Na_2\ SiO_3}}{3}\right]$$

(iii) On the other hand, if Al is in excess of Na, then turn to Ca

C

Ca

(i) $$\frac{x}{2}\,\mathrm{Ca} + x\mathrm{Al} = \frac{3}{2}\,x\mathrm{Cal} = \frac{3}{2}\,x\left[\frac{\mathrm{CaAl_2O_4}}{3}\right].$$

(ii) If Ca remains over after (i) above, then form Cs.

$$y\mathrm{Ca} + \frac{y}{2}\,\mathrm{si} = \frac{3}{2}\,y\mathrm{Cs} = \frac{3}{2}\,y\left[\frac{\mathrm{Ca_2SiO_4}}{3}\right].$$

(iii) If on the other hand, Al remains in excess, then turn to Mg

D

Mg

(i) The basis Sp is formed thus

$$\frac{y}{2}\mathrm{Mg} + y\,\mathrm{Al} = \frac{3}{2}\,y\mathrm{Sp} = \frac{3}{2}\,y\left[\frac{\mathrm{MgAl_2O_4}}{3}\right].$$

(ii) If after Sp is formed, there is yet a balance of Al, then the saturation of Fe is taken to form the basis hercynite (H*z*).

(iii) If on the other hand there is a balance of Mg proceed as directed in (G. i), after going through E and F.

E

Fe''

(i) $\frac{z}{2}\,\text{Fe}'' + z\text{Al} = \frac{3}{2}\,z\text{Hz} = \frac{3}{2}\,z\left[\frac{\text{Fe}''\,\text{Al}_2\text{O}_4}{3}\right].$

(ii) If still Al is in excess, corundum is formed with the balance say, w

$$w.\,\text{Al} = w.\,\text{C} = \frac{w.\ \text{Al}_2\text{O}_3}{2}.$$

(iii) If Fe'' is in excess, proceed as directed under (G. ii) after taking the steps F and (G. i).

F

Fe'''

If Fe''' is present, then convert it to form the silicate Fs thus

$$x\text{Fe}''' + \frac{x}{2}\,\text{Si} = \frac{3}{2}\,x\text{Fs} = \frac{3}{2}\,x\left[\frac{\text{Fe}_2'''\ \text{SiO}_5}{3}\right].$$

G

Mg

(i) The balance of Mg in (D.iii) is converted into the basis forsterite (Fo)

$$x.\text{Mg} + \frac{x}{2}\,\text{Si} = \frac{3}{2}\,x.\ \text{Fo} = \frac{3}{2}\,x\left[\frac{\text{Mg}_2\text{SiO}_4}{3}\right].$$

(ii) After the above step, the balance of Fe'' in E is converted into Fa as follows:

$$x\text{Fe}'' + \frac{x}{2}\,\text{Si} = \frac{3}{2}\,x\text{Fa} = \frac{3}{2}\,x\left[\frac{\text{Fe}_2''\text{SiO}_4}{3}\right].$$

Of the minor constituents,

(i) TiO_2 is considered as basis rutile (Ru).

(ii) ZrO_2 is combined with an equivalent amount of SiO_2 to form the basis 1/2 ZrSiO_4, Zircon (Z).

$$x\text{ZrO}_2 + x\text{SiO}_2 = 2x\cdot\text{Z} = 2x\left[\frac{\text{ZrSiO}_4}{2}\right].$$

(iii) Lastly, the balance of SiO_2 is considered as basis Q. The other minor constituents are disposed of thus:

$x\text{P}_2\text{O}_5$ to form apatite (Cp) $= \frac{5}{2}\,x\text{Cp}$

$x\text{Cl}$ to form halite (Hl) $= x\text{Hl}$

xF to form fluorite (Fr) $= x$Fr

xS to form pyrite (Pr) $= x$Pr

xCr to form chromite (Cr) $= \frac{3}{2} x$Cr

It would therefore be possible to arrive at the following groups of combinations.

TABLE VII

Basis Groups

(in relation to atom numbers)

Alkali excess >Al	K<Al also K+Na>Al	K+Na +2 Ca =Al	K+Na<Al also K+Na+2 Ca>Al	$\text{Al} < \frac{\text{K+Na+2 Ca}}{\text{+2 Fe}''\text{+2 Mg}}$ Al>K+Na+2 Ca	$\text{Al} > \frac{\text{K+Na+2 Ca}}{\text{+2 Fe}''\text{+2 Mg}}$
1	2	3	4	5	6
Kp	Kp	Kp	Kp	Kp	Kp
Ks	Ne	Ne	Ne	Ne	Ne
Ns	Ns	Cal	Cal	Cal	Cal
Cs	Cs		Cs	Sp	Sp
Fs	Fs	Fs	Fs	Fo or Hz	Hz
Fo	Fo	Fo	Fo	Fa	C
Fa	Fa	Fa	Fa	Fs	Fs
Ru	Ru	Ru	Ru	Ru	Ru
Q	Q	Q	Q	Q	Q

Sum up the atom numbers of all constituents.

Determine the percentage of each basis molecule as in

$$\frac{a}{s} \times 100; \quad \frac{b}{s} \times 100, \text{ etc., where}$$

$$a + b + c \ldots\ldots = s.$$

Example.—Hornblende Norite—St. Thomas Mount, Madras. (Analyst —Washington).

Calculation of the basis by distribution of atom numbers.

A glance at the atom numbers shows that

$$\text{K} + \text{Na} < \text{Al}$$

$$\text{K} + \text{Na} + 2\text{Ca} > \text{Al}$$

Hence, the basis of Group 4 will be formed.

TABLE VIII

(*Hornblende Norite—St. Thomas Mcunt*)

Basis

Constituents	Percentage wt.	Atom Nos.	Kp	Ne	Cal	Cs	Fs	Fa	Fo	Ru	Q
SiO_2	50·04	834	19·0	100		43	16·5	109·5	69·75		479·35
Al_2O_3	11·65	229	19·0	100	110						
Fe_2O_3	2·63	33·0					33·0				
FeO	15·76	219						219			
MgO	5·58	139·5							139·5		
CaO	7·89	141			55	86					
Na_2O	3·08	100		100							
K_2O	0·89	19·0	19·0								
TiO_2	1·93	24								24	
P_2O_5*	0·20	2									
H_2O	0·19	11									
Total ..	99·84	1748	57	300	165	129	49·5	328·5	209·25	24	479·35
Basis p.c. $= \times \frac{100}{1748}$			3·26	17·16	9·44	7·38	2·83	18·79	11·95	1·37	27·42
$= \times$ ·0572											99·60

* P_2O_5 —is neglected in calculation

II. From Niggli Values

The basis molecules have been derived from the atom numbers. It is possible to calculate them directly from Niggli values if they are already available.

This involves setting forth the relationship between molecular numbers used in Niggli values and the atom numbers that form the units for the calculation of the basis.

The following table gives the relationship:

TABLE IX

The Atom—The Molecule—Equations

I	II	III	IV	V
Constituents	Symbols		Relationship	Reference Appendix B
	Atoms	Molecules		
SiO_2	Si	si	Si = si	
Al_2O_3	Al	al	Al = 2 al	
Fe_2O_3	Fe'''	fm	Fe = fm.(1−mg)	(1)
FeO	Fe''	mg	Mg = fm (mg)	(2)
MgO	Mg			
CaO	Ca	c	Ca = c	
Na_2O	Na	..	Na = 2 alk (1−k)	(3)
K_2O	K	k	K = 2 alk·k	(4)
TiO_2	Ti	ti	Ti = ti	

$$\Sigma = \text{si} + 2\ \text{al} + \text{fm} + \text{c} + 2\ \text{alk} + \text{ti}$$

$$\text{But al} + \text{fm} + \text{c} + \text{alk} = \frac{m' + n' + p' + q'}{x'} \times 100 \text{ (see p. 2)}$$

$$= 100$$

$$\therefore\ \Sigma = \text{si} + \text{al} + \text{alk} + \text{ti} + 100$$

TABLE X

Basis—Niggli Values, Equations

		Basis	Niggli values	Reference Appendix B
1/3	$KAlSiO_4$	Kp	$6\ alk \cdot k$	(5)
	$NaAlSiO_4$	Ne	$6\ alk\ (1-k)$	(6)
	$CaAlSiO_4$	Cal	$3\ (al-alk)$	(7)
	$CaCaSiO_2$	Cs	$\frac{3}{2}\ (c-al+alk)$	(8)
	$MgMgSiO_4$	Fo	$\frac{3}{2}\ fm \cdot mg$	(9)
	$FeFeSiO_5$	Fs	$\frac{3}{2}\ fm\ (1-mg)$	(10)
	$FeFeSiO_4$	Fa		
1	SiO_2	Q	$si-(50+2\ alk-al)$	(11)
	TiO_2	Ru	ti	

$$\Sigma = 100+si+alk+al+ti$$

TABLE XI

Example

Calculation of the Basis from the Niggli Values

Niggli values (1)	Basis from Niggli value equations (2)			Basis percentage =(2)×100÷246 =(2)×·406 =(3)
	Kp	$= 6\ \text{alk}\cdot\text{k}$ $= 6\times 8\cdot48\times\cdot166$	$= 8\cdot450$	$8\cdot45\times\cdot406 = 3\cdot431$
si = 118·00 al = 16·27	Ne	$= 6\ \text{alk}\ (1-\text{k})$ $= 6\times 8\cdot48\times\cdot834$	$= 42\cdot44$	$42\cdot44\times\cdot406 = 17\cdot230$
fm = 55·30 c = 19·95 alk = 8·48	Cal	$= 3\times(\text{al}-\text{alk})$ $= 3\times(16\cdot27-8\cdot48)$	$= 23\cdot37$	$23\cdot37\times\cdot406 = 9\cdot488$
k = 0·166	Cs	$= \frac{3}{2}\ (\text{c}-\text{al}+\text{alk})$	$= 18\cdot24$	$18\cdot24\times\cdot406 = 7\cdot404$
mg = 0·360	Fo	$= \frac{3}{2}\ \text{fm}\cdot\text{mg}$		
ti = 3·40		$= \frac{3}{2}\times 55\cdot30\times 0\cdot36$	$= 29\cdot86$	$29\cdot86\times\cdot406 = 12\cdot130$
	Fs+Fa	$= \frac{3}{2}\ \text{fm}\ (1-\text{mg})$ $= \frac{3}{2}\times 55\cdot30\times\cdot64$	$= 53\cdot09$	$53\cdot09\times\cdot406 = 21\cdot550$
	Ru	$= \text{ti}$	$= 3\cdot40$	$3\cdot40\times\cdot406 = 1\cdot380$
si	Q	$= \text{si}-(50+2\ \text{alk}-\text{al})$ $= 118-(50+16\cdot96-16\cdot27)$	$= 67\cdot31$	$67\cdot31\times\cdot406 = 27\cdot330$
			246·160	99·943

KATANORMATIVE MINERALS

The minerals of the basis groups are to be considered as fundamental units which have to combine with silica to form the saturated minerals. The minerals formed from the basis in the first instance, according to the prescribed rules mentioned below are called katanormative minerals or katanorms.

The katanorms thus formed may or may not be present in the rock. If they do not give us a picture of the modal percentage of the minerals, the katanorms have to be split or synthesised in such a manner that the modal percentage of minerals results out of the reaction. In this process there will be stages of growth, each stage representing a particular katanorm variant. The aim, however, is to get at the variant corresponding to the mode.

Katanorm—Rules for the Calculation

Bases	Reaction	Katanorm
3 Ns (Na, Na, SiO_3)	1. Ns is combined with an equal quantity of Fs to form: 2 Fns.	Fns (Fns) SiO_4NaFe'''
3 Ks (K, K, SiO_3)	Ks. Do. 2 Fks.	Fks (Fks) SiO_4KFe'''
3 Fs (Fe_2SiO_5)	2. (*a*) 3 Fs $= Fe_2SiO_5$ $= Fe_2O_3+SiO_2$ $= 2\ Hm+1\ Q$	Hm—Hematite (Fe_2O_3)
	(*b*) Mt and Q will result when two units of Fs interact with one unit of Fa as follows: 6 Fs+3 Fa $= Fe_4Si_2O_{10}+Fe_2SiO_4$ $= Fe_6Si_3O_{14}$ $= 2\ Fe_3O_4+3\ SiO_2$ $= 6\ Mt+3\ Q$ Therefore 2 Fs+Fa=2 Mt+1 Q	Mt—Magnetite Fe_3O_4
	(*c*) If more than two units of Fs are available for each unit of Fa, then, both magnetite (Mt) and hematite (Hm) will result as follows: Thus if x units of Fs are left over from 1, let $2y$ units of these combine with y units of Fa to form $2y$ units of Mt and y units of Q. The balance of $(x—2y)$ units of Fs will form $\frac{2}{3}(x—2y)$ of Hm and $\frac{1}{3}(x—2y)$ of Q. We therefore have	

Bases	Reaction	Katanorm
	$x\cdot \mathrm{Fs}+y\cdot \mathrm{Fa}$ $=(x-2y)\ \mathrm{Fs}+y\ (2\ \mathrm{Fs}+\mathrm{Fa})$ $=2y\cdot \mathrm{Mt}+\frac{2}{3}(x-2y)\ \mathrm{Hm}$ $+[y+\frac{1}{3}(x-2y)]\cdot \mathrm{Q}$ where $x>2y$ [*vide* (*a*) & (*b*) above] The liberated Q must be added to the originally present Q and distributed.	Mt & Hm Magnetite & Hematite
3 Cal ($CaAl_2O_4$)	3. If Cal is present, anorthite is obtained. $x\cdot \mathrm{Cal}+\frac{2}{3}x\mathrm{Q}=\frac{5}{3}x\cdot \mathrm{An}$	An Anorthite
3 Cs (Ca_2SiO_4)	4. If Q is present after (3), wollastonite is formed. $x\cdot \mathrm{Cs}+\frac{1}{3}x\cdot \mathrm{Q}=\frac{4}{3}x\cdot \mathrm{Wo}$	Wo Wollastonite
	5. If Q is present after (4), potassic acmite (K·Ac) and Sodic acmite (Ac) are formed.	
Fks	$x\cdot \mathrm{Fks}+\frac{x}{3}\mathrm{Q}=\frac{4}{3}x\cdot \mathrm{K}\cdot \mathrm{Ac}$	Ac Acmite
Fns	$x\cdot \mathrm{Fns}+\frac{x}{3}\mathrm{Q}=\frac{4}{3}x\cdot \mathrm{Ac}$	
3 Ns (Na_2SiO_3)	6. If during the formation of Fks and Fns, Ks, or Ns are left over, then, $x\cdot \mathrm{Ns}+\frac{1}{3}x\mathrm{Q}=\frac{4}{3}x\cdot \mathrm{Ns}'$	Ns' Sodium-di silicate ($Na_2Si_2O_5$)
3 Ks (K_2SiO_3)	$x\cdot \mathrm{Ks}+\frac{1}{3}x\mathrm{Q}=\frac{4}{3}x\cdot \mathrm{Ks}'$	Similarly Ks'
	7. If after all these operations Q still remains, then orthoclase is formed.	
3 Kp ($KAlSiO_4$)	$x\cdot \mathrm{Kp}+\frac{2}{3}x\mathrm{Q}=\frac{5}{3}x\cdot \mathrm{Or}$ *or* Kp may have to be given to a balance of Q, say *y*, in which case $y\mathrm{Q}+\frac{3}{2}y\cdot \mathrm{Kp}=\frac{5}{2}y\cdot \mathrm{Or}$	Or Orthoclase

Bases	Reaction	Katanorm
	8. For a further excess of Q albite is formed.	
3 Ne ($NaAlSiO_4$)	$yQ+\frac{3}{2}y\cdot Ne=\frac{5}{2}Ab$	Ab Albite
	9. If Sp and Hz bases are present and if there is still Q left over, cordierite (cord) is formed.	
3 Sp ($MgAl_2O_4$)	$y\cdot Q+\frac{6}{5}y\cdot Sp=\frac{11}{5}y\cdot Cord$	Cord Cordierite
3 Hz ($FeAl_2O_4$)	$y\cdot Q+\frac{6}{5}y\cdot Hz=\frac{11}{5}y\cdot Fe\text{—}Cord$	
	10. The basis molecules that are left over are Fo, Fa and C. To the extent possible,	
3 Fo (Mg_2SiO_4)	(i) Fo is converted into enstatite (En). Thus $y\cdot Q+3y\cdot Fo=4y\cdot En$	En Enstatite
3 Fa (Fe_2SiO_4)	(ii) Fa is converted into hypersthene $y\cdot Q+3y\cdot Fa=4y\cdot Hy$ and	Hy Hypersthene
2 C (Al_2O_3)	(iii) C is converted into sillimanite (Sil) $y\cdot Q+2y\cdot C=3y\cdot Sil$	Sil Sillimanite

Inasmuch as the basis is calculated to a total of 100, the new assembly of minerals will also give a total of 100.

As has been already said, the ultimate object is to get at such minerals as are actually present in the rock. In the transitional stages, the katanormative minerals may have to pass through hypothetical katavariants.

In special cases, the katamolecular norms are calculated with reference to special theoretical mineral compounds.

The mineral compounds may be made up of a basis molecule and a mineral or two minerals. The following examples are illustrative.

$3\,Kp + 5\,Or = 8\,Lc$ (Leucite)
$3\,Cal + 2\,Wo = 5\,Ge$ (Gehlenite)
$3\,Cal + 1\,Q = 4\,Ts$ (Tschermak's silicate)
$3\,Ne + 8\,En \rightleftharpoons 5\,Ab + 6\,Fo$

EXAMPLE

Hornblende Norite

Calculation of the Katanorm

Basis	.. Kp	Ne	Cal	Cs	Fo	Fs	Fa	Ru	Q
Percentage	.. 3·431	17·230	9·488	7·404	12·130	2·832	18·718	1·380	27·330

Total = 99·95

Calculation	Katanorm	Used Q	Released Q
2 Fs+1 Fa = 2 Mt+1 Q 2·832 Fs+1·416 Fa = 2·832 Mt+1·416 Q	Mt = 2·832	..	1·416
3 Kp+2 Q = 5 Or 3·431 Kp+2·287 Q = 5·718 Or	Or = 5·718	2·287	..
3 Ne+2 Q = 5 Ab 17·230 Ne+11·487 Q=28·716 Ab	Ab = 28·716	11·487	..
3 Cal+2 Q = 5 An 9·488 Cal+6·325 Q =15·813 An	An = 15·813	6·325	..
3 Cs+1 Q = 4 Wo 7·40 Cs+2·46 Q = 9·86 Wo	Wo = 9·860	2·460	..
		22·559	1·416

Total Q available = 27·330 — 22·559 + 1·416 = 6·187.

$$3\text{ Fo} + 1\text{ Q} = 4\text{ En}$$

$$3\text{ Fa} + 1\text{ Q} = 4\text{ Hy} \quad \text{for,}$$

$$1\text{ Q} = 4\ (\text{En} + \text{Hy})$$

$$6{\cdot}187\text{ Q} = 24{\cdot}718\ (\text{En} + \text{Hy})$$

$$\text{En proportional to } \frac{\text{Fo}}{\text{Fo} + \text{Fa}} \text{ (available)}$$

$$= \frac{12{\cdot}130}{12{\cdot}130 + 17{\cdot}302} \times 24{\cdot}78 = 10{\cdot}21$$

$$\text{En} = 10{\cdot}21$$

$$\text{Hy} = 14{\cdot}54$$

$$\text{Fo used for En} = 10{\cdot}21 \times \tfrac{3}{4} = 7{\cdot}56$$

$$\begin{aligned}
\text{Fa used for Hy} &= 14{\cdot}54 \times \tfrac{3}{4} \\
&= 10{\cdot}905 \\
\text{Fo} &= 12{\cdot}130 - 7{\cdot}650 \\
&= 4{\cdot}48 \\
\text{Fa} &= 18{\cdot}718 - (10{\cdot}905 + 1{\cdot}416 \text{ for Mt}) \\
&= 6{\cdot}40 \\
1\ \text{Ru} + 2\ \text{Wo} &= 3\ \text{Tn} \\
1{\cdot}38\ \text{Ru} + 2{\cdot}76\ \text{Wo} &= 4{\cdot}14\ \text{Tn} \\
\therefore\ \text{Tn} &= 4{\cdot}14. \\
\text{Balance of Wo} &= 9{\cdot}86 - 2{\cdot}76 = 7{\cdot}10 \\
\text{Wo} &= 7{\cdot}10.
\end{aligned}$$

Theoretical Katanorm of Hornblende Norite (1)

Katanorm	Or	Ab	An	Wo	En	Hy	Fo	Fa	Tn	Mt	Total
Percentage	5·72	28·72	15·81	7·10	10·21	14·54	4·48	6·40	4·14	2·83	99·95

The katanorm thus derived according to prescribed rules does not reflect to any great extent the mode of the rock, which is composed of andesine, diopside, ortho-pyroxenes, hornblende, and iron ores. Further, sphene, wollastonite and olivine are not present in the rock.

So an attempt must be made to evolve a katavariant which corresponds to that of the mode. In doing so, it is always desirable to take into account the actual analysis of the mineral and its volume percentage if available; a micrometric analysis indicates 20–25% hornblende.

As there is no sphene, in this case, Tn can be split back.

$$4{\cdot}14\ \text{Tn} = 1{\cdot}38\ \text{Ru} + 2{\cdot}76\ \text{Wo}$$

and the katanorm, which is really a katavariant may be rewritten as follows:—

Katavariant (2)

Katanorm	Or	Ab	An	Wo	En	Hy	Fo	Fa	Mt	Ru	Total
Percentage	5·72	28·72	15·81	9·86	10·21	14·54	4·48	6·40	2·83	1·38	99·95

Diopside can be formed thus:

$$\begin{aligned}
2\,\mathrm{Wo} + 2\,(\mathrm{En} + \mathrm{Hy}) &= 4\,\mathrm{Di} \\
9{\cdot}86\,\mathrm{Wo} + 9{\cdot}86\,(\mathrm{En} + \mathrm{Hy}) &= 19{\cdot}72\,\mathrm{Di} \\
\mathrm{En\ in\ Di} &= \frac{10{\cdot}21}{24{\cdot}75} \times 9{\cdot}86 \\
&= 4{\cdot}07 \\
\mathrm{Hy\ in\ Di} &= 5{\cdot}79
\end{aligned}$$

Deducting Wo, En and Hy used, and including Di obtained, the katanorm will be as follows:

Katavariant (3)

Katanorm	Or	Ab	An	Di	En	Hy	Fo	Fa	Mt	Ru	Total
Percentage	5·72	28·72	15·81	19·72	6·14	8·75	4·48	6·40	2·83	1·30	99·95

There is no Q to form Ho which is 20 to 25% in the mode.

Ho is obtained as follows:

$$\begin{aligned}
8\,\mathrm{Di} + 6\,(\mathrm{En} + \mathrm{Hy}) + 1\,\mathrm{Q} + (1\,\mathrm{W}) &= 15\,\mathrm{Ho} \\
\mathrm{Q\ required\ for\ about\ 20\%\ Ho} &= 1{\cdot}35.
\end{aligned}$$

This 1·35 Q can be liberated from Or, Ab and An, proportionately according to their availability.

TABLE XII

Ratio of Released Quartz from Feldspars

	Available from (1)	Quartz released (2)=(1)×1·35÷50·25
Or	5·72	0·154
Ab	28·72	0·771
An	15·81	0·425
Total	50·25	1·350

TABLE XIII

Ratio of Released Kp, Ne and Cal

Quartz released from	Basis	Added constituents to Ho	Constituents to be deducted from (5)	Katanorm	Katavariant =(5)−(4)
(1)	(2)	(3)	(4)	(5)	(6)
Or = 0·154	$\times \frac{3}{2}$ = 0·231 Kp	Kp = 0·231	Or = 0·385	Or = 5·72	Or = 5·33
Ab = 0·772	$\times \frac{3}{2}$ = 1·156 Ne	Ne = 1·156	Ab = 1·927	Ab = 28·72	Ab = 26·79
An = 0·425	$\times \frac{3}{2}$ = 0·638 Cal	Cal = 0·638	An = 1·063	An = 15·81	An = 14·75

Since,

$$8\ \text{Di} + 6\ (\text{En} + \text{Hy}) + 1\ \text{Q} + (1\ \text{W}) = 15\ \text{Ho},$$

$$10{\cdot}8\ \text{Di} + 8{\cdot}1\ (\text{En} + \text{Hy}) + 1{\cdot}35\ \text{Q} + (1{\cdot}35\ \text{W}) = 20{\cdot}25\ \text{Ho}.$$

8·1 (En + Hy) is made up of 3·34 En + 4·76 Hy.

$$\text{En} = \frac{\text{available En}}{\text{available (En + Hy)}} \times 8{\cdot}1 = \frac{6{\cdot}14}{14{\cdot}89} \times 8{\cdot}1$$

$$= 3{\cdot}34$$

$$\text{Hy} \qquad = 4{\cdot}76.$$

Katavariant (4)

Katanorm	Or	Ab	An	Di	En	Hy	Ho	Fo	Fa	Mt	Ru	Total
Percentage	5·33	26·79	14·75	8·92	2·80	3·99	22·28	4·48	6·40	2·83	1·38	99·95

At this stage, it is obvious that as there is no olivine in the rock, Fo and Fa should be converted into the meta-silicates En and Hy.

The feldspars are again indented for SiO_2 required. The Kp, Ne and Cal liberated will be fixed up again in hornblende (Ho).

$$4{\cdot}48\ \text{Fo} + 1{\cdot}49\ \text{Q} = 5{\cdot}97\ \text{En}$$

$$6{\cdot}40\ \text{Fa} + 2{\cdot}13\ \text{Q} = 8{\cdot}53\ \text{Hy}$$

$$\text{Total Q} = 1{\cdot}49 + 2{\cdot}13$$

$$= 3{\cdot}62$$

3·62 Q must be taken proportionately from the available Or, Ab and An,

TABLE XIV

Ratio of further released quartz from feldspars

	Available from (1)	Quartz released (2)=(1)×3·62÷46·87
Or	5·33	0·41
Ab	26·79	2·07
An	14·75	1·14
Total	46·87	3·62

TABLE XV

Ratio of Further Released Kp, Ne and Cal

Quartz released from	Basis	Added constituents to Ho	Constituents to be deducted from (5) =(1)+(3)	Katanorm	Katavariant 6=(5)−(4)
(1)	(2)	(3)	(4)	(5)	(6)
Or = 0·41	× $\frac{3}{2}$ = 0·61 Kp	Kp = 0·61	Or = 1·02	Or = 5·33	Or = 4·31
Ab = 2·07	× $\frac{3}{2}$ = 3·11 Ne	Ne = 3·11	Ab = 5·18	Ab = 26·79	Ab = 21·61
An = 1·14	× $\frac{3}{2}$ = 1·71 Cal	Cal = 1·71	An = 2·85	An = 14·75	An = 11·90

Therefore Ho (final) = 22·28 + 5·43 = 27·71.

The final katavariant values are

Katavariant (5)

Constituents ..	Or	Ab	An	Di	En	Hy	Ho	Mt	Ru	Total
Percentage ..	4·31	21·61	11·90	8·92	8·87	12·52	27·71	2·83	1·38	100·05

It may here be remarked that the necessary Q for the formation of Ho may be released by forming Bi. But in such a process, calculation shows that there is no adequate Q for the formation of about 25 per cent. hornblende; further, it may not perhaps be quite appropriate to form Bi first and later Ho.

CALCULATION OF THE BASIS OF HORNBLENDE

The hornblende derived has a volume percentage of 27·11 and its composition is shown below:

Constituents	.. Kp	Ne	Cal	Di	En	Hy	Q	Total
As a ratio	.. 0·84	4·27	2·35	10·80	3·34	4·76	1·35	27·71

The constituents Di, En and Hy, have to be split into the bases Cs, Fo, Fa and Q as follows:

10·8 Di = 5·40 Wo + 2·48 En + 2·92 Hy.

(The ratio En : Hy is taken from the primary katanorm.)

Then, the composition will be

Constituents	.. Kp	Ne	Cal	Wo	En	Hy	Q	Total
As a ratio	.. 0·84	4·27	2·35	5·4	3·34+ 2·48 5·82	4·76+ 2·92 7·68	1·35	27·71

5·40 Wo = 4·05 Cs + 1·35 Q

5·82 En = 4·37 Fo + 1·45 Q

7·68 Hy = 5·76 Fa + 1·92 Q

Thus the bases are:

Constituents ..	.. Kp	Ne	Cal	Cs	Fo	Fa	Q	Total
As a ratio ..	.. 0·84	4·27	2·35	4·05	4·37	5·76	6·07	27·71

Inclusions of magnetite have not been taken into account in the bases.

Mt = 2·83

Allowing approximately 1·4 Mt for the hornblende as inclusion,

1·40 Fs + 0·70 Fa = 1·40 Mt + 0·70 Q

Thus, we add in the basis of Ho 1·40 Fs and 0·70 Fa and deduct 0·70 Q.

TABLE XVI

Hornblende—Basis

Weight per cent.

Constituents	As a ratio	$\left(\frac{100}{29\cdot 11} \times 3\cdot 435\right)$	C.R.'s analysis
(1)	(2)	(3)	(4)
Kp ..	0·84	2·89	2·44
Ne ..	4·27	14·67	9·16
Cal ..	2·35	8·11	9·20
Cs ..	4·05	13·91	12·10
Fs ..	1·40	4·81	3·00
Fo ..	4·37	14·97	12·00
Fa ..	6·46	22·19	26·40
Q ..	5·37	18·45	23·60
Total ..	29·11	100·00	97·90, 100·00 (approx.)

It is very interesting that the calculated bases of column 3 are in close agreement with the bases given by Rajagopalan, *vide* in column 4, of hornblende from the same area.

CONCLUSION

The principles of Niggli's method outlined for the study of the origin and growth of igneous minerals and rocks is also applicable to the study of the metamorphic minerals and rocks. The genetic relationship between, say, a suite of calc gneisses with calcareous sediments or of aluminous hornfels with aluminous sediments can be cogently and intelligently established from the beginning to the end. A picture of the stages of metamorphic evolution could be drawn. The kata, meso and epizonal norms of a suite come to have great significance.

His methods are coming to be used more and more by petrologists for their interpretative studies. There is life in the variation diagrams prepared by using Niggli's fundamental units. He writes, "The resistance often met with in petrographic circles against a scientific and critical revision of analytical data probably has various causes. Beside the habit of merely taking over the analyst's figures, the fact that a choice must be made between several equally good methods of recalculating analysis-values may have produced a tendency to use none at all."

In Appendix A are given examples of reaction equations of simple and complex minerals. Some of the more important paragenetic mineral assemblages, under epi, meso and katazonal environment are also given.

To conclude, Niggli's treatment of the subject has a unique simplicity and beauty about it, as the method is directed, to understand the probable but hidden cause of the origin of minerals and rocks, before they were ushered out of the melt.

SUMMARY

Modern conceptions on the processes of crystallization of igneous rocks and the processes of recrystallization of metamorphic rocks, have resulted primarily from a knowledge of equilibrium of investigated silicate systems, which mean heterogeneous equilibria conditions. But Niggli considers that homogeneous equilibria conditions in the fluid state control mineral formation.

A critical insight into the factors that govern the formation of minerals is possible by adopting atomic and molecular units as demanded by studies in atomic chemistry. Niggli's classification of rocks is based on Molecular Values.

It has become the accepted practice to use proportions of the molecules such as SiO_2, Al_2O_3, K_2O, etc., in petrological calculations. But Niggli recommends the use of proportions of the cations (silicon and metals). The calculations are made to a total of 100.

Reaction equations are made with coefficients that denote the number of the electro-positive elements. The molecular amount of a mineral thus becomes proportional to the sum of the cations.

Niggli's view is that the modal minerals are evolved by reactions in the melt state and that therefore petrogenetic problems should be directed to get at the mode by a series of reactions. The various stages of the reaction correspond to katavariants, which finally end in a katanorm that can be equated to the mode. Igneous petrogenesis needs drastic changes. The petrographic data must be critically and scientifically studied with a view to the discovery and the expression of natural laws, reliance being placed on atomic chemistry.

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important aspect of petrographic technique, and will be of help to petrographers both in India and elsewhere ".

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APPENDIX A

IMPORTANT ROCK-FORMING MINERALS

Polysilicates

Orthoclase	Or	$3\,\mathrm{Kp} + 2\,\mathrm{Q} = 5\,\mathrm{Or}$	(1)
Albite	Ab	$3\,\mathrm{Ne} + 2\,\mathrm{Q} = 5\,\mathrm{Ab}$	(2)
Anorthite	An	$3\,\mathrm{Cal} + 2\,\mathrm{Q} = 5\,\mathrm{An}$	(3)

Metasilicates

Leucite	Lc	$3\,\mathrm{Kp} + 1\,\mathrm{Q} = 4\,\mathrm{Lc}$	(4)
Wollastonite	Wo	$3\,\mathrm{Cs} + 1\,\mathrm{Q} = 4\,\mathrm{Wo}$	(5)
Hypersthene	Hy	$3\,\mathrm{Fa} + 1\,\mathrm{Q} = 4\,\mathrm{Hy}$	(6)
Enstatite	En	$3\,\mathrm{Fo} + 1\,\mathrm{Q} = 4\,\mathrm{En}$	(7)
Diopside	Di	$2\,\mathrm{Wo} + 2\,\mathrm{En} = 4\,\mathrm{Di}$	(8)
Hedenbergite	Hed	$2\,\mathrm{Wo} + 2\,\mathrm{Hy} = 4\,\mathrm{Hed}$	(9)
Acmite Aegerine	Ac	$3\,\mathrm{Ns} + 2\,\mathrm{Hm} + 3\,\mathrm{Q} = 8\,\mathrm{Ac}$	(10)
Jadeite	Jd	$3\,\mathrm{Ne} + 1\,\mathrm{Q} = 4\,\mathrm{Jd}$	(11)
Augite (special composition)	Aug	$4\,\mathrm{Di} + 3\,\mathrm{Sp} + 1\,\mathrm{Q} = 8\,\mathrm{Aug}$	(12)
Hornblende	Ho	$8\,\mathrm{Di} + 6\,\mathrm{En} + 1\,\mathrm{Q} + (1\,\mathrm{W}) = 15\,\mathrm{Ho}$	(13)
Cordierite	Cord	$6\,\mathrm{Sp} + 5\,\mathrm{Q} = 11\,\mathrm{Cord}$	(14)
	Fe-Cord	$6\,\mathrm{Hz} + 5\,\mathrm{Q} = 11\,\mathrm{Fe\text{-}Cord}$	(15)

Orthosilicates

Cancrinite	Canc	$18\,\mathrm{Ne} + 2\,\mathrm{Cc} = 20\,\mathrm{Canc}$	(16)
Sodalite	Sod	$18\,\mathrm{Ne} + 2\,\mathrm{Hl} = 20\,\mathrm{Sod}$	(17)
Hauynite	Hau	$18\,\mathrm{Ne} + 4\,\mathrm{A} = 22\,\mathrm{Hau}$	(18)
$CaSO_4$ anhydrite	A		
Nosean	Nos	$18\,\mathrm{Ne} + 3\,\mathrm{Th} = 21\,\mathrm{Nos}$	(19)
Na_2SO_4 thenardite	Th		
Grossularite	Gro	$5\,\mathrm{An} + 3\,\mathrm{Cs} = 8\,\mathrm{Gro}$	(20)
Pyrope	Pyp	$11\,\mathrm{Cord} + 8\,\mathrm{En} = 16\,\mathrm{Pyp} + 3\,\mathrm{Q}$	(21)
Almandite	Alm	$11\,\mathrm{Fe\text{-}Cord} + 8\,\mathrm{Hy} = 16\,\mathrm{Alm} + 3\,\mathrm{Q}$	(22)
Andradite	Andr	$6\,\mathrm{Wo} + 2\,\mathrm{Hm} = 8\,\mathrm{Andr}$	(23)
Forsterite	Fo	Basis	(24)

Fayalite	Fa	Basis	(25)
Larnite	Cs	Basis	(26)
Monticellite	Mont	3 Cs + 3 Fo = 6 Mont	(27)
Meionite	Me	15 An + 1 Cc = 16 Me	(28)
Marialite	Ma	15 Ab + 1 Hl = 16 Ma	(29)
$3NaAlSi_3O_8$—NaCl			
$3NaAlSi_3O_8$ $\frac{1}{2}Na_2SO_4$		30 Ab + 3 Th = 33 Ma	(30)
$3NaAlSi_3O_8$ $\frac{1}{2}Na_2CO_3$		30 Ab + 2 Nc = 32 Ma	(31)
Gehlinite	Ge	3 Cal + 2 Wo = 5 Ge	(32)
Akermanite	Ak	3 Cs + 2 En = 5 Ak	(33)
Vesuvianite $Ca_{10}Al_4(Mg, Fe)_2$ $Si_9O_{34}(OH, F)_4$	Ves	18 (Cs, Fo) + 6 Sil + 1 Q + (2 W) = 25 Ves	(34)
Sillimanite Andalusite Kyanite	Sil	2 C + 1 Q = 3 Sil	(35)
Zoisite	Zo	9 Cal + 2 Wo + 5 Q + (1 W) = 16 Zo	(36)
Epidote	Ep (*l*) = Fe-Ep	6 Cal + 4 Wo + 2 Hm + 4 Q + (1W) = 16 Ep (*l*)	(37)
Analcite	Anc	4 Jd + (1 W) = 4 Anc	(38)
Staurolite	Staur	3 Hz + 3 Sil + 1 Q + (1 W) = 7 Staur	(39)
Muscovite	Ms	10 Or + 4 C + (2 W) = 14 Ms	(40)
Biotite	Fe-Bi	6 Kp + 9 Fa + 1 Q + (2 W) = 16 Bi	(41)
Phlogopite	Mg-Bi= Pgp	6 Kp + 9 Fo + 1 Q + (2 W) = 16 Pgp	(42)
Siderophyllite ($H_4K_2Fe_5Al_4Si_5O_{24}$)	Sdro	6 Kp + 10 Hy + 3 Sil + (2 W) = 16 Sdro + 3 Q	(43)
Chloritoid Ottrelite	Ottr	3 Hz + 1 Q + (2 W) = 4 Ottr	(44)
Serpentine	Serp	3 Fo + 2 En + (2 W) = 5 Serp	(45)
Talc	Tc	6 En + 1 Q + (1 W) = 7 Tc	(46)
Kaolin	Ka	3 Sil + 1 Q + (2 W) = 4 Ka	(47)
Titanite	Tit	1 Ru + 2 Wo = 3 Tit	(48)

Tschermak Silicates

$CaAl_2SiO_6$ .. Ts $3\ Cal + 1\ Q = 4\ Ts$ (49)

$MgAl_2SiO_6$ .. Mg-Ts $3\ Sp + 1\ Q = 4\ Mg\text{-}Ts$ (50)

EXAMPLES OF COMPLEX REACTIONS

Paragenetic Associations

A. Epizonal Minerals

1. *Serpentinization* $6\ Fo + (2\ W) + (CO_2) = 5\ Serp + 1\ Mgs$ (51)

Magnesite .. Mgs $9\ Fo + 1\ Q + (4\ W) = 10\ Serp$ (52)

Periclase .. Ps $15\ Fo + (4\ W) = 10\ Serp + 4\ Ps + 1\ Q$ removed in solution (53)

2. *Steatization* .. $10\ Serp + (3\ CO_2) = 7\ Tc + 3\ Mgs + (2\ W)$ (54)

(Grammatite) Gram
Tremolite
Dolomite .. Dol

$15\ Gram + (4\ CO_2) = 4\ Dol + 7\ Tc + 4\ Q$ (55)

3. *Steatization—Carbonatization* $10\ Serp + (6\ CO_2) = 3\ Mgs + 7\ Tc + (3\ CO_2) + (2\ W)$ or $6\ Mgs + 4\ Q + (4\ W)$ (56)

4. *Kaolinization*

Kaolin .. Kaol
Potas. Carbonate Kc

$30\ Or + (6\ W) + (3\ CO_2) = 12\ Kaol + 6\ Kc + 12\ Q$ (57)

5. *Albitization* .. $5\ An + 2\ Nc + 4\ Q = 10\ Ab + 1\ Cc$ (58)

Sodium Carbonate Nc

Epi-Mesozonal Minerals

6. *Decarbonization* (Progressive)

$6\ Dol + 4\ Q + (W) = 7\ Tc + 3\ Cc + (3\ CO_2)$ (59)

$14\ Tc + 3\ Cc = 15\ Ho + 2\ Dol + (CO_2) + (H_2O)$ (60)

7. *Carbonization* .. 3 Cc + 8 Bi + 6 Q = 12 Di + 5 Or + (1 W) + 3 CO_2) (61)

Mesozonal Minerals

Anthophyllite ..	Anth	45 Anth + 56 Di + 4 Q + (4 W) = 105 Ho	(62)
Tremolite ..	Ho		
Almandite ..	Alm	8 Hy + 11 Fe-Cord = 16 Alm + 3 Q	(63)
		8 Fe-Bi + 6 Sil + 1 Q = 7 Ms + 8 Alm	(64)
Staurolite ..	Staur	8 Alm + 15 Sil + (1 W)=21 Staur+2 Q	(65)
Muscovite ..	Ms.	8 Fe-Bi + 21 Sil + (W) = 7 Ms + 21 Staur + 1 Q	(66)
		11 Fe-Cord + 2 Hm + (W) = 7 Staur + 3 Mt + 3 Q	(67)

Katazonal Minerals

Forsterite ..	Fo	4 Dol + 1 Q = 2 Cc + 3 Fo + (2 CO_2)	(68)
Cordierite ..	Cord	42 Ms + 16 Bi + 15 Q = 40 Or + 33 Cord + (8 W)	(69)
Sapphirinization			
Sapphirine ..	Sphr	3 Fo + 12 En + 16 C + 1 Q = 11 cord + 21 Sphr	(70)
Sillimanite ..	Sil	10 An + 12 Fo + 4 Di + 3 Q = 8 Gro + 18 (En + Hy) + 3 Sil	(71)
Enstatite ..	En	10 An + 18 Fo + 4 Di + 3 Q = 8 Gro + 3 Sp + 24 En	(72)
Pyrope ..	Pyr	10 An + 16 En = 16 Pyp + 8 Di + 2 Q	(73)
Spinel ..	Sp	5 An + 4 Di = 3 Sp + 4 Wo + 2 Q	(74)
Sapphirinization ..		15 An + 28 En + 12 Wo + 36 Sp + 5 Q + (2 W) = 30 Anth + 42 Sphr + 24 Gro	(75)
Phlogopitization			
Phlogopite ..	(Mg-Bi) Pyp	18 Sp + 20 En + 4 Q + 4 $KO_{\frac{1}{2}}$ + (4 W) = 14 Sphr + 32 Mg-Bi	(76)

APPENDIX B

$$\text{fm} = \text{FeO} + 2\,\text{Fe}_2\text{O}_3 + \text{MgO}$$

$$\text{Fe} = \text{FeO} + 2\,\text{Fe}_2\text{O}_3$$

$$\text{Fe} = \text{fm} - \text{MgO}$$

$$\text{mg} = \frac{\text{MgO}}{\text{fm}}$$

$$\text{Fe} = \text{fm} - \text{fm}\cdot\text{mg}$$

$$\text{Fe} = \text{fm}\,(1 - \text{mg}) \qquad (1)$$

$$\text{mg} = \frac{\text{MgO}}{\text{fm}} \text{ or } \frac{\text{Mg}}{\text{fm}}$$

$$\text{Mg} = \text{fm}\cdot\text{mg} \qquad (2)$$

$$\text{alk} = \text{Na}_2\text{O} + \text{K}_2\text{O}$$

$$\text{k} = \frac{\text{K}_2\text{O}}{\text{Na}_2\text{O} + \text{K}_2\text{O}}$$

$$\text{Na}_2\text{O} = \text{alk} - \text{K}_2\text{O}$$

$$\text{K}_2\text{O} = \text{k}\,(\text{K}_2\text{O} + \text{Na}_2\text{O}) = \text{k}\cdot\text{alk}$$

$$\text{Na}_2\text{O} = \text{alk} - \text{k}\cdot\text{alk} = \text{alk}\,(1 - \text{k})$$

$$\text{Na} = 2\,\text{alk}\,(1 - \text{k})$$

[Na_2O — molecular number to be multiplied by 2 to get atom numbers. alk (1 – k) is molecular number.] (3)

$$\text{K}_2\text{O} = \text{k}\cdot\text{alk}$$

$$\text{K} = 2\,\text{alk}\cdot\text{k}$$

(K_2O — molecular numbers to be multiplied by 2 to get atom numbers. k·alk value is in molecular numbers.) (4)

$$\text{K} = 2\,\text{alk}\cdot\text{k}$$

$$\text{Kp} = 3\,\text{K} = 6\,\text{alk}\cdot\text{k} \qquad (5)$$

$$\mathrm{Na} = 2\,\mathrm{alk}\,(1-\mathrm{k})\ \text{(see 3)}$$

$$\mathrm{Ne} = 3\,\mathrm{Na}$$

$$\mathrm{Ne} = 6\,\mathrm{alk}\,(1-\mathrm{k}) \tag{6}$$

Atom numbers of Al_2O_3 are distributed to CaO, only after satisfying K_2O and Na_2O.

$$\text{Available Al} = 2\,(\mathrm{al}-\mathrm{alk})$$

$$\mathrm{Cal} = \frac{3}{2}\,\mathrm{Al}$$

$$= 3\,(\mathrm{al}-\mathrm{alk}) \tag{7}$$

Cs is formed from CaO, left over after CaO allotment to Cal

Ca allotted to Cal = al − alk

Ca balance for Cs = (c − al + alk)

$$\mathrm{Cs} = \frac{3}{2}\,(\mathrm{c}-\mathrm{al}+\mathrm{alk}) \tag{8}$$

$$\mathrm{Fo} = \frac{3}{2}\,\text{Mg atoms}$$

$$= \frac{3}{2}\,\mathrm{fm}\cdot\mathrm{mg}\ \text{(see 2)} \tag{9}$$

$$\mathrm{Fe} = \mathrm{fm}\,(1-\mathrm{mg}) \qquad (\textit{see}\ 1)$$

$$\mathrm{Fs} + \mathrm{Fa} = \frac{3}{2}\,\mathrm{fm}\,(1-\mathrm{mg})$$

Fs + Fa contain each

$\frac{3}{2}$ Fs and Fa atoms respectively. (10)

$$\mathrm{Q} = \mathrm{si} - (50 + 2\,\mathrm{alk} - \mathrm{al})$$

This value of Q is obtained as follows:

Q is the balance of atoms left over after forming the other bases.

Total available atoms

= si + 100 + al + alk + ti (*see* Table IX) (*a*)

Total atoms distributed to basis molecules

$$= 3\text{ alk} + \frac{3}{2}\text{ al} + \frac{3}{2}\text{ c} + \frac{3}{2}\text{ alk} + \frac{3}{2}\text{ fm} + \text{ti}$$

$$= 3\text{ alk} + \text{ti} + \frac{3}{2}(\text{al} + \text{c} + \text{alk} + \text{fm})$$

Since al + c + alk + fm = 100

$$= 3\text{ alk} + \text{ti} + \frac{3}{2} \times 100$$

$$= 3\text{ alk} + \text{ti} + 150 \qquad (b)$$

Deducting (*b*) from (*a*)

$$\text{si} - 50 - 2\text{ alk} + \text{al}$$

$$\therefore\ Q = \text{si} - (50 + 2\text{ alk} - \text{al}) \qquad (11)$$