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## **The Norm, its Variations, their Calculation and Relationships**

By *Charles S. Hutchison*, Kuala Lumpur\*)

With 2 tables in the text

### **Abstract**

Systematic differences between the standard C.I.P.W. weight percent norm, the Niggli catanorm and the volume norm are presented. Complete rules are given for their calculation and conversions. Rules are given for a weight percent norm which includes biotite and hornblende and its conversion to the mesonorm and volume norm. The appropriate application of the various norms is discussed.

### **INTRODUCTION**

The norm is a powerful petrographic tool which is especially valuable for describing and classifying volcanic rocks which are not wholly crystalline. It is customary for petrologists to recalculate rock analyses to a norm. Resulting from this practice it has been found that variation diagrams of rock suites are better constructed on a norm-dependant parameter such as the differentiation index of THORNTON and TUTTLE (1960) or the crystallization index of POLDERVAART and PARKER (1964) rather than on a weight percent parameter derived from the chemical analysis.

There are three major norm variations: the C.I.P.W. weight percent norm (JOHANSEN, 1931), the Niggli catanorm (BARTH, 1962a) and the mesonorm (BARTH, 1962b). The C.I.P.W. norm is generally universally preferred by North American petrologists and the catanorm by European. The mesonorm is a special variation which has particular application to selected rocks. Because of tradition, very few petrologists are familiar with each of the norm variations. This article shows that the norm variations are very simply related and can be readily converted one to the other.

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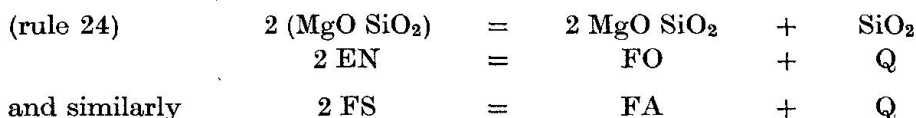
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## THE C.I.P.W. NORM

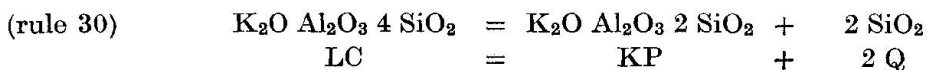
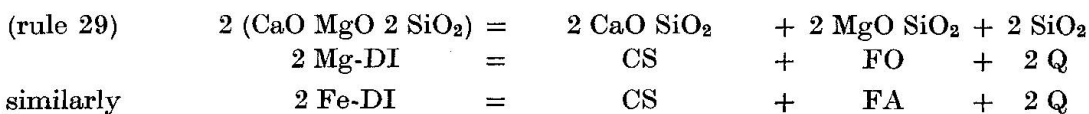
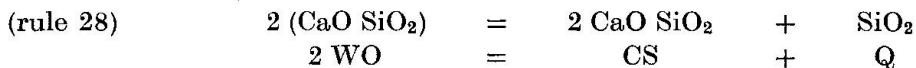
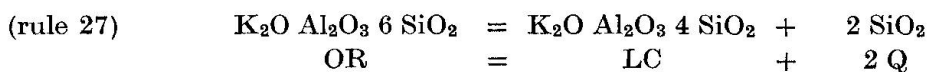
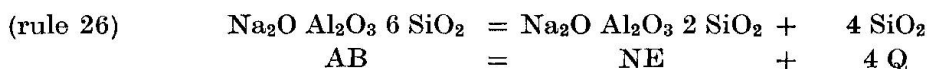
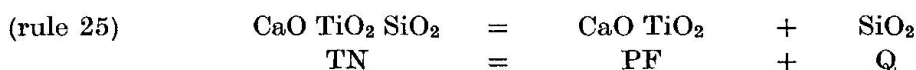
The original norm is that of C. W. Cross, J. P. Iddings, L. V. Pirsson and H. S. Washington. The first complete compilation of the rules for its calculation was given by JOHANNSEN (1931) but it is only when faced with writing the rules logically for computer calculation that an unambiguous set of rules became available. KELSEY (1965) gave such a set of rules. Even then, they contain a few ambiguities which have been removed by the present author. A definitive set of C.I.P.W. rules is given in the appendix to this paper in a form readily convertible to computer language and capable of being applied by any person who can reliably perform simple arithmetic. A few improvements have been made to facilitate subsequent calculation of the crystallization index.

*Meaning:* The C.I.P.W. norm is an expression of the total rock chemistry in terms of the selected normative minerals expressed in *weight proportions* of the minerals. If the norm is finally recalculated to 100% anhydrous, as is common practice for better comparison, then the norm gives the weight % of the normative minerals.

The basis of the C.I.P.W. norm is well illustrated by the equations used to effect desilification when, after forming diopside or hypersthene (rule 22 in the Appendix), it is found that an excessive molecular proportion of  $\text{SiO}_2$  has been allocated.



In the norm, 2MgO (molecular proportion) is both equal to 2 EN or 1 FO, whereas  $\text{SiO}_2$  is equal to EN, FS, FO, FA or Q (in the desilification rules, Q = D).



The normative parameter differentiation index (THORNTON and TUTTLE, 1960) is defined based upon the C.I.P.W. norm and *not* on any other variation. Hence to avoid confusion it should not be calculated from any other norm. Similarly the crystallization index (POLDERVAART and PARKER, 1964) is based only on the C.I.P.W. norm. The C.I.P.W. norm may equally be referred to as the weight percent norm. It is appropriate to plot weight percent chemical parameters, such as  $K_2O$  %, total alkali % etc., against normative parameters based on the C.I.P.W. norm and not the Niggli norm.

### THE NIGGLI CATANORM

Originally evolved by P. Niggli, the first set of readily available rules were compiled by BARTH (1962a). A logical set of rules, suitable for computer programming, is given by HUTCHISON (1974).

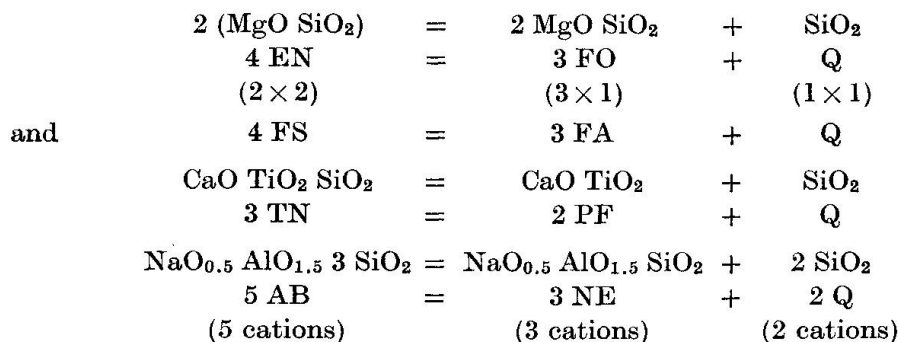
*Meaning:* The catanorm expresses the total rock chemistry in terms of the selected normative minerals expressed in cation proportions. For example, an oversimplified norm which gives albite 50 %, anorthite 50 % means that the cation proportions of  $Na_{0.5} AlO_{1.5} 3 SiO_2$  and  $CaO 2 AlO_{1.5} 2 SiO_2$  are equal. Both normative minerals have a total of 5 cations per molecule. Hence the cation proportions can be calculated as:

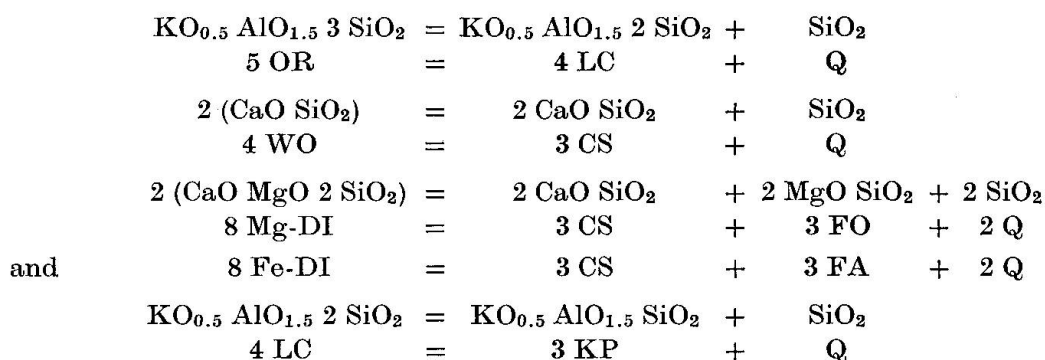
in albite  $Na \frac{1}{5}$  of 50 = 10.  $Al \frac{1}{5}$  of 50 = 10.  $Si \frac{3}{5}$  of 50 = 30.  
in anorthite  $Ca \frac{1}{5}$  of 50 = 10.  $Al \frac{2}{5}$  of 50 = 20.  $Si \frac{2}{5}$  of 50 = 20.

Hence the total cation proportions are Na 10, Ca 10, Al 30, Si 50.

The catanorm is closer to a volume norm (= mode) than the C.I.P.W. norm. If all normative minerals had identical atomic structure so that their specific gravities depended only upon their cation contents, then the catanorm would represent a volume norm. However the specific gravity of a mineral is dependant not just on the cation content but also on detailed atomic structure, hence the catanorm is not exactly equal to the volume norm.

The basis of the catanorm can be illustrated by the equations used to effect desilification.





It is appropriate to plot cation proportions derived from the total rock analysis against normative parameters based on the Niggli and not the C.I.P.W. norm. Weight based oxides should be compared only with weight based normative parameters (C.I.P.W.), whereas molecular or cationic proportions should be compared with the cation based norm (catanorm).

#### THE BARTH MESONORM

The rules for the mesonorm (a variation of the catanorm) were given by BARTH (1962b) and set out logically by HUTCHISON (1974). It is identical in meaning to the catanorm, and differs from it only in the introduction of the few minerals given in table 2. Because potassium is allocated to biotite, the normative amount of orthoclase (obtained by the catanorm) is reduced. Hornblende (actinolite + edenite + riebeckite) will also partly take the place of diopside and hypersthene. The mesonorm is suitable for granitic to dioritic rocks and for metamorphosed igneous rocks in which biotite and hornblende are more appropriate than diopside and hypersthene. The mesonorm allocates less  $\text{SiO}_2$  to form biotite and hornblende than the catanorm or C.I.P.W. norm would do in forming diopside and hypersthene. Hence the mesonorm consistently has more Q, or for undersaturated rocks lesser amounts of undersaturated minerals than the other norms. These fundamental differences make the mesonorm more appropriate for granites, granodiorites, diorites and amphibolites.

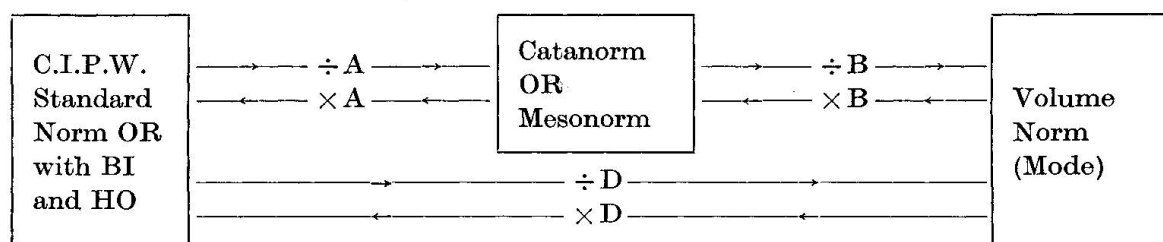
#### SYSTEMATIC RELATIONSHIP BETWEEN THE NORMS

Conversion from the C.I.P.W. to the catanorm is relatively simple. Hence there is no real need to compute different norms independantly. A systematic scheme is given for conversion between the norms. Since the C.I.P.W. norm is perhaps the most widely used, it will be taken as the starting point, and complete rules for its calculation are given in the appendix.

First choose whether to calculate the standard weight % C.I.P.W. norm or the modified weight % C.I.P.W. norm which includes biotite and hornblende. The choice will depend on whether an assemblage free of biotite and hornblende (e.g. basic igneous rocks) is more appropriate than one with biotite and hornblende (e.g. acid to intermediate igneous rocks and meta-igneous rocks). Having made the appropriate choice, calculate the C.I.P.W. norm according to the rules in the appendix. Normative-based parameters such as D.I. and C.I. must be based on the standard C.I.P.W. and not on the biotite-hornblende variation. It is best to end with an 100% anhydrous norm in which the total normative minerals is 100.

Table 1 gives the conversion factors required to change from the C.I.P.W. weight % norm to the catanorm (cation proportion norm) or a truly volume norm, which should be directly comparable with the mode (if the modal and normative minerals are identical). Likewise if we have already obtained a catanorm, it can be converted to a C.I.P.W. weight % or volume norm. A rock mode could be converted to a norm using the appropriate D factors. The conversion scheme is:

for each mineral in turn



Where the factors A, B, and D are given in Tables 1 and 2.

Then pro-rate to 100% by multiplying each mineral by  $\frac{100 \times \text{mineral}}{\text{total of minerals}}$ .

The conversion factors have been so calculated as to end with closely similar normative totals after conversion, so that the final proration to 100% results in only a very slight change in the amounts. The basis for the conversion is that a comparison of a large number of norms shows that orthoclase is closely similar in amount irrespective of which norm is calculated. Hence a conversion factor between C.I.P.W. and the catanorm for OR was taken as 1.000.

The derivation of the A, D, and B factors of table 1 is illustrated by an example. Factor A for albite =  $\frac{30.99 + 50.98 + 3 (60.08)}{5} \times \text{constant}$ . The constant for all minerals is  $\frac{5}{47.10 + 50.98 + 3 (60.08)}$ , so that all conversions are relative to orthoclase.  $D = \frac{\text{the mineral specific gravity}}{2.57}$  (2.57 is the specific gravity of orthoclase).  $B = \frac{D}{A}$ .

Table 1. *Normative minerals and conversion factors for the C.I.P.W. standard norm, the catanorm and the volume norm*

Symbol	Normative mineral	Cations	Formula	A	D	B
<i>Salic group</i>						
Q	quartz	1	SiO <sub>2</sub>	1.079	1.031	0.955
C	corundum	1	AlO <sub>1.5</sub>	0.916	1.564	1.708
Z	zircon	2	ZrO <sub>2</sub> SiO <sub>2</sub>	1.646	1.821	1.106
OR	orthoclase	5	KO <sub>0.5</sub> AlO <sub>1.5</sub> 3 SiO <sub>2</sub>	1.000	1.000	1.000
AB	albite	5	NaO <sub>0.5</sub> AlO <sub>1.5</sub> 3 SiO <sub>2</sub>	0.942	1.019	1.082
AN	anorthite	5	CaO 2 AlO <sub>1.5</sub> 2 SiO <sub>2</sub>	1.000	1.074	1.074
LC	leucite	4	KO <sub>0.5</sub> AlO <sub>1.5</sub> 2 SiO <sub>2</sub>	0.980	0.965	0.985
NE	nepheline	3	NaO <sub>0.5</sub> AlO <sub>1.5</sub> SiO <sub>2</sub>	0.851	1.012	1.189
KP	kalsilite	3	KO <sub>0.5</sub> AlO <sub>1.5</sub> SiO <sub>2</sub>	0.947	1.016	1.072
HL	halite	2	Na Cl	0.525	0.840	1.601
<i>Femic group</i>						
AC	acmite	4	NaO <sub>0.5</sub> FeO <sub>1.5</sub> 2 SiO <sub>2</sub>	1.037	1.381	1.331
NS	sodium metasilicate	3	2 NaO <sub>0.5</sub> SiO <sub>2</sub>	0.731	1.019	1.395
KS	potassium meta-silicate	3	2 KO <sub>0.5</sub> SiO <sub>2</sub>	0.924	1.070	1.158
WO	wollastonite	2	CaO SiO <sub>2</sub>	1.043	1.109	1.063
EN	enstatite	2	MgO SiO <sub>2</sub>	0.902	1.249	1.385
FS	ferrosilite	2	FeO SiO <sub>2</sub>	1.185	1.541	1.300
FO	forsterite	3	2 MgO SiO <sub>2</sub>	0.843	1.253	1.487
FA	fayalite	3	2 FeO SiO <sub>2</sub>	1.220	1.708	1.400
CS	larnite	3	2 CaO SiO <sub>2</sub>	1.031	1.288	1.249
MT	magnetite	3	FeO 2 FeO <sub>1.5</sub>	1.387	2.016	1.454
CM	chromite	3	FeO 2 CrO <sub>1.5</sub>	1.340	1.981	1.478
HM	hematite	1	FeO <sub>1.5</sub>	1.435	2.043	1.424
IL	ilmenite	2	FeO TiO <sub>2</sub>	1.363	1.829	1.342
TN	sphene	3	CaO TiO <sub>2</sub> SiO <sub>2</sub>	1.174	1.362	1.160
PF	perovskite	2	CaO TiO <sub>2</sub>	1.221	1.568	1.284
RU	rutile	1	TiO <sub>2</sub>	1.435	1.634	1.139
AP	apatite	8	5 CaO 3 PO <sub>2.5</sub>	1.108	1.265	1.142
FR	fluorite	3	CaO 2 F	0.563	1.237	2.196
PR	pyrite	3	FeO 2 S	0.814	1.953	2.399
CC	calcite	2	CaO CO <sub>2</sub>	0.863	1.054	1.222
CT	cassiterite	1	SnO <sub>2</sub>	2.707	2.724	1.006
SP	{Mg-SP spinel	3	MgO 2 AlO <sub>1.5</sub>	0.852	1.381	1.621
	{Fe-SP hercynite	3	FeO 2 AlO <sub>1.5</sub>	1.041	1.712	1.645
DI	{Mg-DI diopside	4	CaO MgO 2 SiO <sub>2</sub>	0.973	1.253	1.288
	{Fe-DI hedenbergite	4	CaO FeO 2 SiO <sub>2</sub>	1.114	1.385	1.243

Table 2. *Additional normative minerals and conversion factors for the weight % norm (with biotite and hornblende), the mesonorm and the volume norm*

Symbol	Normative mineral	Cations	Formula	A	D	B
BI	{Mg-BI phlogopite	8	KO <sub>0.5</sub> 3 MgO AlO <sub>1.5</sub> 3 SiO <sub>2</sub>	0.897	1.074	1.197
	{Fe-BI annite	8	KO <sub>0.5</sub> 3 FeO AlO <sub>1.5</sub> 3 SiO <sub>2</sub>	1.109	1.167	1.052
ACT	{Mg-ACT tremolite	15	2 CaO 5 MgO 8 SiO <sub>2</sub>	0.951	1.175	1.236
	{Fe-ACT ferro-actinolite	15	2 CaO 5 FeO 8 SiO <sub>2</sub>	1.140	1.339	1.175
ED	{Mg-ED edenite	16	NaO <sub>0.5</sub> 2 CaO 5 MgO AlO <sub>1.5</sub> 7 SiO <sub>2</sub>	0.916	1.187	1.296
	{Fe-ED ferro-edenite	16	NaO <sub>0.5</sub> 2 CaO 5 FeO AlO <sub>1.5</sub> 7 SiO <sub>2</sub>	1.094	1.362	1.245
RI	riebeckite	15	2 NaO <sub>0.5</sub> 2 FeO <sub>1.5</sub> 3 FeO 8 SiO <sub>2</sub>	1.099	1.323	1.204

$$HO = ACT + ED + RI$$

Table 2 lists additional conversion factors which will be required if the norms containing biotite and hornblende are used. For these norms, the factors of table 1 apply and table 2 gives only the additional minerals needed.

The following are important fundamental differences and similarities between the norms:

1. The standard C.I.P.W. norm gives identical normative minerals to the catanorm, but the relative amounts differ. Where A of table 1 is close to 1.00, there will be little difference between the normative amounts. The greater the divergence from unity, the greater the normative difference. If A is less than unity, the amount in the catanorm will be greater than the amount in the C.I.P.W. norm and vice-versa.
2. Rock classifications based on norms, such as the basalt classification of YODER and TILLEY (1962) and GREEN and RINGWOOD (1967) should be equally valid based on either the C.I.P.W. or the catanorm, although they were defined on a C.I.P.W. basis.
3. Ratios in a mineral isomorphous series are properly calculated from the catanorm, e.g. plagioclase  $Ab_xAn_{100-x}$ , hypersthene  $En_xFs_{100-x}$  and olivine  $FO_xFA_{100-x}$ . The proportions of the end members obtained in the C.I.P.W. norm may be recalculated to cation proportions x and 100 - x by using the factors A of table 1 without recalculation of the whole norm.
4. Relative plots of quartz, albite, orthoclase for granitic rocks are best based on mesonorm calculations because the C.I.P.W. standard norm over-allocates to the orthoclase molecule.

#### Appendix A: Rules for calculation of the standard C.I.P.W. weight % norm, crystallization and differentiation index

1. Calculate the amounts (molecular proportions) of the oxides and elements present in the analysis by dividing each given weight percentage by the appropriate following formula weight:

SiO <sub>2</sub>	60.08	TiO <sub>2</sub>	79.90	Al <sub>2</sub> O <sub>3</sub>	101.96	ZrO <sub>2</sub>	123.22	Fe <sub>2</sub> O <sub>3</sub>	159.69	
MnO	70.94	FeO	71.85	NiO	74.71	MgO	40.31	BaO	153.34	CaO 56.08
SrO	103.62	Na <sub>2</sub> O	61.98	Cr <sub>2</sub> O <sub>3</sub>	151.98	K <sub>2</sub> O	94.20	Cl	35.45	SO <sub>3</sub> 80.06
P <sub>2</sub> O <sub>5</sub>	141.94	F	19.00	CO <sub>2</sub>	44.01	S	32.06	SnO <sub>2</sub>	150.69	

2. Add the (MnO + NiO) amount to the FeO amount.

3. Add the (BaO + SrO) amount to the CaO amount.

In the following rules the oxides or elements referred to are the amounts obtained for them after applying rules 1 to 3 above. All normative minerals are taken as of zero amount until formed by the following rules applied consecutively.

4. Make Z = ZrO<sub>2</sub>. Make Y = Z.

Throughout the norm calculation, amounts will be allocated to Y. The final total of Y is required at rule 23.

5. If  $\text{CaO} \geq 10/3 \text{ P}_2\text{O}_5$   
 Make  $\text{AP} = \text{P}_2\text{O}_5$   
 Subtract  $10/3 \text{ AP}$  from  $\text{CaO}$   
 If  $\text{CaO} < 10/3 \text{ P}_2\text{O}_5$   
 Make  $\text{AP} = 3/10 \text{ CaO}$   
 Subtract  $\text{AP}$  from  $\text{P}_2\text{O}_5$   
 $\text{CaO}$  becomes zero  
 Excess  $\text{P}_2\text{O}_5$  weight % in rock  
 $= 141.94 \text{ P}_2\text{O}_5$
6. If  $\text{F} \geq 2/3 \text{ AP}$   
 Subtract  $2/3 \text{ AP}$  from  $\text{F}$   
 If  $\text{F} < 2/3 \text{ AP}$   
 Make  $\text{F} = \text{zero}$
7. If  $\text{CaO} \geq 0.5 \text{ F}$   
 Make  $\text{FR} = 0.5 \text{ F}$   
 Subtract  $\text{FR}$  from  $\text{CaO}$   
 If  $\text{CaO} < 0.5 \text{ F}$   
 Make  $\text{FR} = \text{CaO}$ . Subtract  $2 \text{ FR}$  from  $\text{F}$   
 $\text{CaO}$  becomes zero  
 Excess  $\text{F}$  weight % in rock  $= 19.00 \text{ F}$
8. If  $\text{Na}_2\text{O} \geq 0.5 \text{ Cl}$   
 Make  $\text{HL} = \text{Cl}$   
 Subtract  $0.5 \text{ HL}$  from  $\text{Na}_2\text{O}$   
 If  $\text{Na}_2\text{O} < 0.5 \text{ Cl}$   
 Make  $\text{HL} = 2 \text{ Na}_2\text{O}$   
 Subtract  $\text{HL}$  from  $\text{Cl}$   
 $\text{Na}_2\text{O}$  becomes zero  
 Excess  $\text{Cl}$  weight % in rock  $= 35.45 \text{ Cl}$
9. If  $\text{FeO} \geq 0.5 \text{ S}$  (or  $0.5 \text{ SO}_3$ )  
 Make  $\text{PR} = 0.5 \text{ S}$  (or  $0.5 \text{ SO}_3$ )  
 Subtract  $\text{PR}$  from  $\text{FeO}$   
 If  $\text{FeO} < 0.5 \text{ S}$  (or  $0.5 \text{ SO}_3$ )  
 Make  $\text{PR} = \text{FeO}$   
 Subtract  $2 \text{ PR}$  from  $\text{S}$  (or  $\text{SO}_3$ )  
 $\text{FeO}$  becomes zero  
 Excess  $\text{S}$  in weight %  $= 32.06 \text{ S}$   
 (excess  $\text{SO}_3$  in weight %  $= 80.06 \text{ SO}_3$ )
10. If  $\text{CaO} \geq \text{CO}_2$   
 Make  $\text{CC} = \text{CO}_2$   
 Reduce  $\text{CaO}$  by amount  $\text{CC}$   
 If  $\text{CaO} < \text{CO}_2$   
 Make  $\text{CC} = \text{CaO}$   
 Reduce  $\text{CO}_2$  by amount  $\text{CC}$   
 $\text{CaO}$  becomes zero  
 Excess  $\text{CO}_2$  weight % in rock  $= 44.01 \text{ CO}_2$
11. If  $\text{FeO} \geq \text{Cr}_2\text{O}_3$   
 Make  $\text{CM} = \text{Cr}_2\text{O}_3$   
 Reduce  $\text{FeO}$  by amount  $\text{CM}$   
 If  $\text{FeO} < \text{Cr}_2\text{O}_3$   
 Make  $\text{CM} = \text{FeO}$   
 Reduce  $\text{Cr}_2\text{O}_3$  by amount  $\text{CM}$   
 $\text{FeO}$  becomes zero  
 Excess  $\text{Cr}_2\text{O}_3$  weight % in rock  
 $= 151.98 \text{ Cr}_2\text{O}_3$
12. If  $\text{FeO} \geq \text{TiO}_2$   
 Make  $\text{IL} = \text{TiO}_2$   
 Reduce  $\text{FeO}$  by amount  $\text{IL}$   
 $\text{TiO}_2$  becomes zero  
 If  $\text{FeO} < \text{TiO}_2$   
 Make  $\text{IL} = \text{FeO}$   
 Reduce  $\text{TiO}_2$  by amount  $\text{IL}$   
 $\text{FeO}$  becomes zero
13. Make  $\text{CT} = \text{SnO}_2$
14. If  $\text{Al}_2\text{O}_3 \geq \text{K}_2\text{O}$   
 Make  $\text{OR} = \text{K}_2\text{O}$   
 Reduce  $\text{Al}_2\text{O}_3$  by amount  $\text{OR}$   
 Increase  $\text{Y}$  by amount  $6 \text{ OR}$   
 If  $\text{Al}_2\text{O}_3 < \text{K}_2\text{O}$   
 Make  $\text{OR} = \text{Al}_2\text{O}_3$   
 Reduce  $\text{K}_2\text{O}$  by amount  $\text{OR}$   
 $\text{Al}_2\text{O}_3$  becomes zero  
 Make  $\text{KS} = \text{K}_2\text{O}$   
 Increase  $\text{Y}$  by amount  $(6 \text{ OR} + \text{KS})$

15. If  $\text{Al}_2\text{O}_3 \geq \text{Na}_2\text{O}$   
 Make  $\text{AB} = \text{Na}_2\text{O}$   
 Reduce  $\text{Al}_2\text{O}_3$  by amount  $\text{AB}$   
 $\text{Na}_2\text{O}$  becomes zero  
 Increase  $\text{Y}$  by amount 6  $\text{AB}$
- If  $\text{Al}_2\text{O}_3 < \text{Na}_2\text{O}$   
 Make  $\text{AB} = \text{Al}_2\text{O}_3$   
 Reduce  $\text{Na}_2\text{O}$  by amount  $\text{AB}$   
 $\text{Al}_2\text{O}_3$  becomes zero  
 Increase  $\text{Y}$  by amount 6  $\text{AB}$
16. If  $\text{Na}_2\text{O} \geq \text{Fe}_2\text{O}_3$   
 Make  $\text{AC} = \text{Fe}_2\text{O}_3$   
 $\text{Fe}_2\text{O}_3$  becomes zero  
 Reduce  $\text{Na}_2\text{O}$  by amount  $\text{AC}$   
 Make  $\text{NS} = \text{Na}_2\text{O}$   
 Increase  $\text{Y}$  by amount  $(4 \text{ AC} + \text{NS})$
- If  $\text{Na}_2\text{O} < \text{Fe}_2\text{O}_3$   
 Make  $\text{AC} = \text{Na}_2\text{O}$   
 Reduce  $\text{Fe}_2\text{O}_3$  by amount  $\text{AC}$   
 Increase  $\text{Y}$  by amount 4  $\text{AC}$
17. If  $\text{Al}_2\text{O}_3 \geq \text{CaO}$   
 Make  $\text{AN} = \text{CaO}$   
 $\text{CaO}$  becomes zero  
 Reduce  $\text{Al}_2\text{O}_3$  by amount  $\text{AN}$   
 Increase  $\text{Y}$  by amount 2  $\text{AN}$   
 Make  $\text{C} = \text{Al}_2\text{O}_3$
- If  $\text{Al}_2\text{O}_3 < \text{CaO}$   
 Make  $\text{AN} = \text{Al}_2\text{O}_3$   
 Reduce  $\text{CaO}$  by amount  $\text{AN}$   
 Increase  $\text{Y}$  by amount 2  $\text{AN}$
18. If  $\text{CaO} \geq \text{TiO}_2$   
 Make  $\text{TN} = \text{TiO}_2$   
 Reduce  $\text{CaO}$  by amount  $\text{TN}$   
 Increase  $\text{Y}$  by amount  $\text{TN}$
- If  $\text{CaO} < \text{TiO}_2$   
 Make  $\text{TN} = \text{CaO}$   
 $\text{CaO}$  becomes zero  
 Reduce  $\text{TiO}_2$  by amount  $\text{TN}$   
 Make  $\text{RU} = \text{TiO}_2$   
 Increase  $\text{Y}$  by amount  $\text{TN}$
19. If  $\text{Fe}_2\text{O}_3 \geq \text{FeO}$   
 Make  $\text{MT} = \text{FeO}$   
 $\text{FeO}$  becomes zero  
 Reduce  $\text{Fe}_2\text{O}_3$  by amount  $\text{MT}$   
 Make  $\text{HM} = \text{Fe}_2\text{O}_3$
- If  $\text{Fe}_2\text{O}_3 < \text{FeO}$   
 Make  $\text{MT} = \text{Fe}_2\text{O}_3$   
 Reduce  $\text{FeO}$  by amount  $\text{MT}$
20. Make  $(\text{MgFe}) = (\text{MgO} + \text{FeO})$ . Calculate  $\text{PrMg} = \frac{\text{MgO}}{\text{MgO} + \text{FeO}}$  and  $\text{PrFe} = \frac{\text{FeO}}{\text{MgO} + \text{FeO}}$
21. This rule is to be applied *only* if the weight percent of  $\text{SiO}_2$  in the rock is less than 45.00 (that is the rock is ultrabasic). If  $\text{SiO}_2$  weight % > 45.00, omit this rule and proceed to rule 22.
- If  $(\text{MgFe}) \leq \text{C}$   
 Make  $\text{Mg-SP} = \text{PrMg} (\text{MgFe})$   
 Make  $\text{Fe-SP} = \text{PrFe} (\text{MgFe})$   
 Reduce  $\text{C}$  by amount  $(\text{Mg-SP} + \text{Fe-SP})$   
 $(\text{MgFe})$  becomes zero
- If  $(\text{MgFe}) > \text{C}$   
 Make  $\text{Mg-SP} = \text{PrMg} (\text{C})$   
 Make  $\text{Fe-SP} = \text{PrFe} (\text{C})$   
 $\text{C}$  becomes zero  
 Reduce  $(\text{MgFe})$  by amount  $(\text{Mg-SP} + \text{Fe-SP})$
22. If  $\text{CaO} \geq (\text{MgFe})$   
 Make  $\text{Mg-DI} = \text{PrMg} (\text{MgFe})$   
 Make  $\text{Fe-DI} = \text{PrFe} (\text{MgFe})$   
 Reduce  $\text{CaO}$  by amount  $(\text{Mg-DI} + \text{Fe-DI})$
- If  $\text{CaO} < (\text{MgFe})$   
 Make  $\text{Mg-DI} = \text{PrMg} (\text{CaO})$   
 Make  $\text{Fe-DI} = \text{PrFe} (\text{CaO})$   
 Reduce  $(\text{MgFe})$  by amount  $(\text{Mg-DI} + \text{Fe-DI})$

- Make WO = CaO  
Increase Y by amount  
2 (Mg-DI + Fe-DI) + WO
23. If  $\text{SiO}_2 \geq Y$   
Make Q =  $\text{SiO}_2 - Y$   
Omit rules 24 to 30  
Go directly to rule 31
24. If  $D \leq 0.5 (EN + FS)$   
Make FO = PrMg (D)  
Make FA = PrFe (D)  
Reduce EN by amount PrMg (2 D)  
Reduce FS by amount PrFe (2 D)  
D becomes zero. Omit rules 25–30  
Go directly to rule 31
25. If  $D \leq TN$   
Make PF = D  
Reduce TN by amount D  
D becomes zero. Omit rules 26–30  
Go directly to rule 31
26. If  $D \leq 4 AB$   
Make NE = D/4  
Reduce AB by amount D/4  
D becomes zero. Omit rules 27–30  
Go directly to rule 31
27. If  $D \leq 2 OR$   
Make LC = 0.5 D  
Reduce OR by amount 0.5 D  
D becomes zero. Omit rules 28–30  
Go directly to rule 31
28. If  $D \leq 0.5 WO$   
Make CS = D  
Reduce WO by amount 2 D  
D becomes zero. Omit rules 29–30  
Go directly to rule 31
29. If  $D \leq (\text{Mg-DI} + \text{Fe-DI})$   
Increase CS by amount 0.5 D  
Increase FO by amount 0.5 D (PrMg)  
Increase FA by amount 0.5 D (PrFe)  
Reduce Mg-DI by amount D (Pr-Mg)  
Reduce Fe-DI by amount D (PrFe)  
D becomes zero. Omit rule 30  
Go directly to rule 31
- Make EN = PrMg (MgFe)  
Make FS = PrFe (MgFe)  
Increase Y by amount  
2 (Mg-DI + Fe-DI) + EN + FS
- If  $\text{SiO}_2 < Y$   
Make Q = zero  
Make D =  $Y - \text{SiO}_2$   
Continue with the following rules until D becomes zero
- If  $D > 0.5 (EN + FS)$   
Make FO = 0.5 EN  
Make FA = 0.5 FS  
Reduce D by amount 0.5 (EN + FS)  
EN becomes zero  
FS becomes zero  
Continue with rule 25
- If  $D > TN$   
Make PF = TN  
Reduce D by amount TN  
TN becomes zero  
Proceed with rule 26
- If  $D > 4 AB$   
Make NE = AB  
Reduce D by amount 4 AB  
AB becomes zero  
Proceed with rule 27
- If  $D > 2 OR$   
Make LC = OR  
Reduce D by amount 2 OR  
OR becomes zero  
Proceed with rule 28
- If  $D > 0.5 WO$   
Make CS = 0.5 WO  
Reduce D by amount 0.5 WO  
WO becomes zero  
Proceed with rule 29
- If  $D > (\text{Mg-DI} + \text{Fe-DI})$   
Increase CS by an amount  
0.5 (Mg-DI + Fe-DI)  
Increase FO by amount 0.5 (Mg-DI)  
Increase FA by amount 0.5 (Fe-DI)  
Reduce D by amount (Mg-DI + Fe-DI)  
Mg-DI becomes zero  
Fe-DI becomes zero  
Proceed with rule 30

30. If  $D \leq 2 LC$   
 Make  $KP = 0.5 D$   
 Reduce  $LC$  by amount  $0.5 D$   
 $D$  now becomes zero  
 Go to rule 31.
- If  $D > 2 LC$   
 Make  $KP = LC$   
 Reduce  $D$  by amount  $2 LC$   
 $LC$  becomes zero.  
 $D$  is the amount of over-allocated silica.  
 Desilification should continue until  $D$  becomes zero. This rule is so very unlikely to apply that no rules have been formulated. Go to 31.
31. Convert each normative mineral amount obtained by the foregoing rules to a normative mineral weight % by multiplying each mineral amount by the corresponding molecular weight given in the following list:
- |    |        |    |        |    |        |    |        |    |        |    |        |
|----|--------|----|--------|----|--------|----|--------|----|--------|----|--------|
| Q  | 60.08  | C  | 101.96 | Z  | 183.30 | OR | 556.64 | AB | 524.42 | AN | 278.20 |
| LC | 436.48 | NE | 284.10 | KP | 316.32 | HL | 58.44  |    |        |    |        |
- The total of the foregoing minerals gives the weight % of the salic group (SALIC)
- |       |        |       |        |    |        |       |        |       |        |
|-------|--------|-------|--------|----|--------|-------|--------|-------|--------|
| AC    | 461.99 | NS    | 122.06 | KS | 154.28 | Mg-DI | 216.55 | Fe-DI | 248.09 |
| WO    | 116.16 | EN    | 100.39 | FS | 131.93 | FO    | 140.70 | FA    | 203.78 |
| MT    | 231.54 | CM    | 223.84 | IL | 151.75 | HM    | 159.69 | TN    | 196.06 |
| RU    | 79.90  | AP    | 336.21 | FR | 78.08  | PR    | 119.98 | CC    | 100.09 |
| Mg-SP | 142.27 | Fe-SP | 173.81 |    |        |       |        | CT    | 150.69 |
- The total of the foregoing minerals gives the weight % of the femic group (FEMIC).  
 The norm obtained will not total  $SALIC + FEMIC = 100$  because the rock chemical analysis was used as given, and  $H_2O$  in the rock analysis was not utilized.
32. To recalculate the norm to 100% anhydrous, each of the normative minerals obtained in rule 31 should be multiplied by  $\frac{100}{Salic + Femic}$ . The values of Salic and Femic obtained in rule 31 can also be multiplied by the same  $\frac{100}{Salic + Femic}$ .
- To complete the norm,  $HY$  takes the place of  $(EN + FS)$ .  $OL$  the place of  $(FO + FA)$   $DI$  the place of  $(Mg-DI + Fe-DI)$  and  $SP$  the place of  $(Mg-SP + Fe-SP)$ .
33. The Differentiation Index (D.I.) of THORNTON and TUTTLE (1965) =  $Salic - AN$  (both determined in Rule 32).
34. The Crystallization Index (C.I.) of POLDERVAART and PARKER (1964) =  $AN + Mg-DI + FO + 0.700837 (EN) + Mg-SP$  (all determined in rule 32).

#### Appendix B: Rules for calculation of the weight % norm (with biotite and hornblende)

- I. Perform rules 1 to 11 (inclusive) of the standard C.I.P.W. norm
- II. Make  $CT = SnO_2$
- III. If  $TiO_2 \leq CaO$   
 Make  $TN = TiO_2$   
 Reduce  $CaO$  by amount  $TN$   
 Add  $TN$  to  $Y$   
 $TiO_2$  becomes zero
- If  $TiO_2 > CaO$   
 Make  $TN = CaO$   
 Reduce  $TiO_2$  by amount  $TN$   
 Add  $TN$  to  $Y$   
 $CaO$  becomes zero

- IV. If  $\text{FeO} \geq \text{TiO}_2$   
 Make  $\text{IL} = \text{TiO}_2$   
 Reduce  $\text{FeO}$  by amount  $\text{IL}$   
 $\text{TiO}_2$  becomes zero
- If  $\text{FeO} < \text{TiO}_2$   
 Make  $\text{IL} = \text{FeO}$   
 Reduce  $\text{TiO}_2$  by amount  $\text{IL}$   
 $\text{FeO}$  becomes zero  
 Make  $\text{RU} = \text{TiO}_2$
- V. Perform rules 14 and 15 of the standard C.I.P.W. norm
- VI. Either: If  $\text{Fe}_2\text{O}_3 \leq 1/3 \text{ FeO}$   
 If  $\text{Na}_2\text{O} \leq \text{Fe}_2\text{O}_3$   
 Make  $\text{RI} = \text{Na}_2\text{O}$   
 Reduce  $\text{Fe}_2\text{O}_3$  by amount  $\text{RI}$   
 Reduce  $\text{FeO}$  by amount  $3 \text{ RI}$   
 Increase  $\text{Y}$  by amount  $8 \text{ RI}$   
 $\text{Na}_2\text{O}$  becomes zero
- If  $\text{Na}_2\text{O} > \text{Fe}_2\text{O}_3$   
 Make  $\text{RI} = \text{Fe}_2\text{O}_3$   
 Reduce  $\text{Na}_2\text{O}$  by amount  $\text{RI}$   
 Reduce  $\text{FeO}$  by amount  $3 \text{ RI}$   
 Increase  $\text{Y}$  by amount  $8 \text{ RI}$   
 $\text{Fe}_2\text{O}_3$  becomes zero
- Or: If  $\text{Fe}_2\text{O}_3 > 1/3 \text{ FeO}$   
 If  $\text{Na}_2\text{O} \leq 1/3 \text{ FeO}$   
 Make  $\text{RI} = \text{Na}_2\text{O}$   
 Reduce  $\text{Fe}_2\text{O}_3$  by amount  $\text{RI}$   
 Reduce  $\text{FeO}$  by amount  $3 \text{ RI}$   
 Increase  $\text{Y}$  by amount  $8 \text{ RI}$   
 $\text{Na}_2\text{O}$  becomes zero
- If  $\text{Na}_2\text{O} > 1/3 \text{ FeO}$   
 Make  $\text{RI} = 1/3 \text{ FeO}$   
 Reduce  $\text{Na}_2\text{O}$  by amount  $\text{RI}$   
 Reduce  $\text{Fe}_2\text{O}_3$  by amount  $\text{RI}$   
 Increase  $\text{Y}$  by amount  $8 \text{ RI}$   
 $\text{FeO}$  becomes zero
- VII. Make  $\text{NS} = \text{Na}_2\text{O}$ . Increase  $\text{Y}$  by an amount  $\text{NS}$
- VIII. Perform rules 19, 20 and 21 of the standard C.I.P.W. norm
- IX. Perform rule 17 of the standard C.I.P.W. norm
- X. If  $(\text{MgFe}) \leq 6 \text{ OR}$   
 Make  $\text{Mg-BI} = 1/6 (\text{PrMg}) (\text{MgFe})$   
 Make  $\text{Fe-BI} = 1/6 (\text{PrFe}) (\text{MgFe})$   
 Reduce  $\text{OR}$  by amount  
 $(\text{Mg-BI} + \text{Fe-BI})$   
 $(\text{MgFe})$  becomes zero
- If  $(\text{MgFe}) > 6 \text{ OR}$   
 Make  $\text{Mg-BI} = \text{PrMg} (\text{OR})$   
 Make  $\text{Fe-BI} = \text{PrFe} (\text{OR})$   
 Reduce  $(\text{MgFe})$  by amount  
 $6 (\text{Mg-BI} + \text{Fe-BI})$   
 $\text{OR}$  becomes zero
- XI. If  $(\text{MgFe}) \leq 5/2 \text{ CaO}$   
 Make  $\text{Mg-ACT} = 1/5 \text{ PrMg} (\text{MgFe})$   
 Make  $\text{Fe-ACT} = 1/5 \text{ PrFe} (\text{MgFe})$   
 Reduce  $\text{CaO}$  by amount  
 $2 (\text{Mg-ACT} + \text{Fe-ACT})$   
 $(\text{MgFe})$  becomes zero  
 Make  $\text{WO} = \text{CaO}$   
 Increase  $\text{Y}$  by amount  
 $8 (\text{Mg-ACT} + \text{Fe-ACT}) + \text{WO}$   
 $\text{CaO}$  becomes zero
- If  $(\text{MgFe}) > 5/2 \text{ CaO}$   
 Make  $\text{Mg-ACT} = 0.5 \text{ PrMg} (\text{CaO})$   
 Make  $\text{Fe-ACT} = 0.5 \text{ PrFe} (\text{CaO})$   
 Reduce  $(\text{MgFe})$  by amount  
 $5 (\text{Mg-ACT} + \text{Fe-ACT})$   
 $\text{CaO}$  becomes zero  
 Make  $\text{EN} = \text{PrMg} (\text{MgFe})$   
 Make  $\text{FS} = \text{PrFe} (\text{MgFe})$   
 Increase  $\text{Y}$  by amount  
 $8 (\text{Mg-ACT} + \text{Fe-ACT}) + \text{EN} + \text{FS}$
- XII. If  $\text{SiO}_2 \geq \text{Y}$   
 Make  $\text{Q} = \text{SiO}_2 - \text{Y}$   
 Omit rules XIII to XVI  
 Go directly to rule XVII
- If  $\text{SiO}_2 < \text{Y}$   
 Make  $\text{Q} = \text{zero}$   
 Make  $\text{D} = \text{Y} - \text{SiO}_2$   
 Continue with rule XIII

XIII. Either: If  $(\text{Mg-ACT} + \text{Fe-ACT}) \geq 2 \text{ AB}$ If  $\text{AB} \geq \text{D}/8$ Make  $\text{Mg-ED} = \text{PrMg} (\text{D}/8)$ Make  $\text{Fe-ED} = \text{PrFe} (\text{D}/8)$ Reduce  $\text{Mg-ACT}$  by amount  $2 \text{ Mg-ED}$ Reduce  $\text{Fe-ACT}$  by amount  $2 \text{ Fe-ED}$ Reduce  $\text{AB}$  by amount $(\text{Mg-ED} + \text{Fe-ED})$  $\text{D}$  becomes zero.

Omit rules XIV to XVI

Go directly to rule XVII

If  $\text{AB} < \text{D}/8$ Make  $\text{Mg-ED} = \text{PrMg} (\text{AB})$ Make  $\text{Fe-ED} = \text{PrFe} (\text{AB})$ Reduce  $\text{Mg-ACT}$  by amount  $2 \text{ Mg-ED}$ Reduce  $\text{Fe-ACT}$  by amount  $2 \text{ Fe-ED}$ Reduce  $\text{D}$  by amount $8 (\text{Mg-ED} + \text{Fe-ED})$  $\text{AB}$  becomes zero

Continue with rule XIV

Or: If  $(\text{Mg-ACT} + \text{Fe-ACT}) < 2 \text{ AB}$ If  $(\text{Mg-ACT} + \text{Fe-ACT}) \geq \text{D}/4$ Make  $\text{Mg-ED} = \text{PrMg} (\text{D}/8)$ Make  $\text{Fe-ED} = \text{PrFe} (\text{D}/8)$ Reduce  $\text{Mg-ACT}$  by amount  $2 \text{ Mg-ED}$ Reduce  $\text{Fe-ACT}$  by amount  $2 \text{ Fe-ED}$ Reduce  $\text{AB}$  by amount $(\text{Mg-ED} + \text{Fe-ED})$  $\text{D}$  becomes zero

Omit rules XIV to XVI

Go directly to rule XVII

If  $(\text{Mg-ACT} + \text{Fe-ACT}) < \text{D}/4$ Make  $\text{Mg-ED} = 0.5 \text{ Mg-ACT}$ Make  $\text{Fe-ED} = 0.5 \text{ Fe-ACT}$ Reduce  $\text{AB}$  by amount $(\text{Mg-ED} + \text{Fe-ED})$ Reduce  $\text{D}$  by amount  $8 (\text{Mg-ED} + \text{Fe-ED})$  $\text{Mg-ACT}$  becomes zero $\text{Fe-ACT}$  becomes zero

Continue with rule XIV

XIV. If  $\text{D} \leq 0.5 (\text{EN} + \text{FS})$ Make  $\text{FO} = \text{PrMg} (\text{D})$ Make  $\text{FA} = \text{PrFe} (\text{D})$ Reduce  $\text{EN}$  by amount  $2 \text{ FO}$ Reduce  $\text{FS}$  by amount  $2 \text{ FA}$  $\text{D}$  becomes zero. Omit rules XV to XVI. Go directly to rule XVIIIf  $\text{D} > 0.5 (\text{EN} + \text{FS})$ Make  $\text{FO} = 0.5 \text{ EN}$ Make  $\text{FA} = 0.5 \text{ FS}$ Reduce  $\text{D}$  by amount  $0.5 (\text{EN} + \text{FS})$  $\text{EN}$  becomes zero.  $\text{FS}$  becomes zero

Continue with rule XV

XV. Either: If  $(\text{FO} + \text{FA}) \leq 0.5 \text{ C}$ If  $(\text{FO} + \text{FA}) \geq \text{D}$ Increase  $\text{Mg-SP}$  by amount  $2 \text{ PrMg} (\text{D})$ Increase  $\text{Fe-SP}$  by amount  $2 \text{ PrFe} (\text{D})$ Reduce  $\text{C}$  by amount  $2 \text{ D}$ Reduce  $\text{FO}$  by amount  $\text{PrMg} (\text{D})$ Reduce  $\text{FA}$  by amount  $\text{PrFe} (\text{D})$  $\text{D}$  becomes zero. Omit rule XVI

Go directly to rule XVII

If  $(\text{FO} + \text{FA}) < \text{D}$ Increase  $\text{Mg-SP}$  by amount  $2 \text{ FO}$ Increase  $\text{Fe-SP}$  by amount  $2 \text{ FA}$ Reduce  $\text{C}$  by amount  $2 (\text{FO} + \text{FA})$ Reduce  $\text{D}$  by amount  $(\text{FO} + \text{FA})$  $\text{FO}$  becomes zero $\text{FA}$  becomes zero

Continue with rule XVI

Or: If  $(\text{FO} + \text{FA}) > 0.5 \text{ C}$ If  $\text{C} \geq 2 \text{ D}$ Increase  $\text{Mg-SP}$  by amount  $2 \text{ PrMg} (\text{D})$ Increase  $\text{Fe-SP}$  by amount  $2 \text{ PrFe} (\text{D})$ Reduce  $\text{C}$  by amount  $2 \text{ D}$ Reduce  $\text{FO}$  by amount  $\text{PrMg} (\text{D})$ Reduce  $\text{FA}$  by amount  $\text{PrFe} (\text{D})$  $\text{D}$  become zero. Omit rule XVI

Go directly to rule XVII.

If  $\text{C} > 2 \text{ D}$ Increase  $\text{Mg-SP}$  by amount  $2 \text{ PrMg} (\text{C})$ Increase  $\text{Fe-SP}$  by amount  $2 \text{ PrFe} (\text{C})$ Reduce  $\text{D}$  by amount  $0.5 \text{ C}$ Reduce  $\text{FO}$  by amount  $0.5 \text{ PrMg} (\text{C})$ Reduce  $\text{FA}$  by amount  $0.5 \text{ PrFe} (\text{C})$  $\text{C}$  becomes zero

Continue with rule XVI.

XVI. If  $D \leq 4 AB$ Make  $NE = D/4$ Reduce  $AB$  by amount  $D/4$  $D$  becomes zero. Proceed with rule

## XVII

If  $D > 4 AB$ Make  $NE = AB$ Reduce  $D$  by amount  $4 AB$  $AB$  becomes zero.

There are no further rules for desilification. The  $D$  remaining is the excess  $SiO_2$  over-allocated. This rule is very unlikely to apply.

Go to rule XVII.

XVII. Convert each normative mineral amount obtained by the foregoing rules to a normative mineral weight % by multiplying each mineral amount by the corresponding molecular weight given in rule 31 of the standard C.I.P.W. norm. The following are the additional molecular weights required in the Femic group.

Mg-BI	798.50	Fe-BI	987.74	Mg-ACT	794.35	Fe-ACT	952.05
Mg-ED	1632.48	Fe-ED	1947.88	RI	917.87		

Salic is exactly as in rule 31. Femic includes the above minerals in addition to those of rule 31.

XVIII. Recalculate the norm to 100% anhydrous and make  $HY$ ,  $OL$  and  $SP$  as in rule 32. In addition make  $BI = (Mg-BI + Fe-BI)$ ,  $ACT = (Mg-ACT + Fe-ACT)$ ,  $ED = (Mg-ED + Fe-ED)$ , and finally hornblende ( $HO$ ) =  $ACT + ED + RI$ . The  $D.I.$  and  $C.I.$  should not be calculated from this norm variation but only from the standard C.I.P.W. norm.

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