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Mesonorms of granitic rock analyses

G. R. PARSLOW, B.SC., PH.D., F.G.S.
Department of Geology and Geography, Kingston College of Technology
Kingston-upon-Thames

SUMMARY. A modification to the CIPW norm, to account for the presence of biotite or muscovite or both in granite rocks, is described. The modification is most significant in norms that have been reduced to three components and plotted on experimental phase diagrams, such as the systems Q–Or–Ab and Or–Ab–An.

SINCE Cross, Iddings, Pirsson, and Washington (1903) first published their system of deriving normative minerals from chemical analyses, the CIPW norm has been successfully used to identify, compare, and classify trends in igneous rocks with similar or differing mineral compositions. The norm has been used for metamorphic rocks and rocks of somewhat uncertain mode of origin (Bowes, 1967). Various minor modifications to the CIPW norm have been advocated (Eskola, 1954; Barth, 1959; Kelsey, 1965), and the further modification presented here is considered desirable when chemical data for granitic rocks are to be compared graphically with phase diagrams. This paper represents an expansion, into the igneous field, of Barth's (1962) mesonorm calculation. The basis of his mesonorm calculation, unfortunately a rather neglected technique, is that certain metamorphic rocks require mica and amphibole representation in normative calculations. Recently, Barth (1966) indicated the desirability of modifying CIPW norms of granitic rocks in conjunction with the quinary system An–Ab–Or–Q–H_2O. A footnote in Dunham *et al.* (1965, p. 394) indicates that a similar modification was used for analyses of the Weardale granite.

Problems arising from the use of CIPW norms of granitic rocks in conjunction with phase diagrams

In recent years, the advent of extensive experimental studies has led to research workers utilizing the CIPW norm as a means of defining actual rock analyses in terms of phase diagrams. The resultant diagrams are generally accepted as aids for the understanding of the petrogenetic features of sets of data. However, the percentages of the CIPW normative molecules for a given rock will only approximate the actual molecules used in a particular phase diagram; thus, in general the normative constituents are defined in different terms to the diagrams upon which they are plotted. This anomaly is usually small enough to be ignored except for rocks of granitic affiliation where the CIPW norm will allocate[1] all K^+ to Or, all Na^+ to Ab, and all Ca^{2+} (less the

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[1] Throughout the text the normative minerals are referred to in the form of the standard abbreviations; Bt and Mu represent normative biotite and muscovite.

small amount in Ap) to An; thus errors will be introduced as a function of the modal percentages of the non-felsic K^+-, Na^+-, and Ca^{2+}-bearing minerals in granitic rocks.

The ternary diagrams commonly quoted in granitic studies are the Q–Ab–Or and An–Ab–Or systems and their variants under different pressures of water vapour. The former diagram has been fully investigated by Tuttle and Bowen (1958) and by Luth, Jahns, and Tuttle (1964); the An–Ab–Or system has been defined as accurately as possible, as a three-component projection of the system Q–An–Ab–Or, by Kleeman (1965) from the work of Yoder, Stewart, and Smith (1957), Stewart (1958), and Luth, Jahns, and Tuttle (1964).

The above systems can be considered as a felsic magma containing no femic constituents. If a natural granite is now considered it is found to contain, ignoring minor constituents, felsic material, which is directly comparable with the artificial system, plus a small amount of femic material. This material will appear in the CIPW norm as Hy, Il, Mt, and possibly Di, whilst modally it appears as one or more of the minerals biotite, chlorite, muscovite, magnetite. The granite will therefore give a CIPW norm in which the felsic constituents tend to be over-estimated; these and other discrepancies between modal and normative minerals are now considered.

Biotite. Since biotite contains approximately 10 % K^+, a granite containing 10 % of this mineral will have a CIPW norm in which Or is about 5 % too high.

Chlorite. In the present context chlorite can be classed as biotite since it is nearly always secondary after the latter mineral in granitic rocks and therefore develops by post-magmatic processes after the felsic components have crystallized. Evidence for its secondary nature is seen in its close association with biotite in granites. Solid-state development of chlorite is also indicated by recent experimental work (Fawcett and Yoder, 1966). This work shows that the stability field of an average 'igneous' chlorite will not extend into the liquid field above the minimum melting curve for granite except at pressures in excess of 5 kb.

Muscovite. This mineral contains slightly more than 11 % K^+ and therefore a granite containing 5 % modal muscovite will have 4–5 % too much Or in the CIPW norm. Care must be taken to ensure, by means of optical fabric studies, that any white mica present can be identified as either primary or secondary (or possibly a mixture of both types). If the mica is secondary (sericite or paragonite) no anomaly is present in the standard CIPW norm as the mica formed after the felsic minerals; primary muscovite, however, requires a modification of the CIPW norm.

Lattice groupings. In addition to the obvious failings mentioned above, micas have smaller ratios of cations to 'anionic groups' than normative pyroxene and olivine, thus transferring the potential anomaly to the distribution of Si^{4+} and Al^{3+}. Since the change in lattice grouping is taken up by an increase of Al^{3+} and the appearance of OH^- in the 'anionic group', a correction would increase Q and decrease C, an excess of which is very common in CIPW norms of granites, and result in a more accurate representation of elemental distribution in granitic rocks.

Ilmenite. The CIPW norm assumes all Ti^{4+} in a rock will be present in the form of this mineral. This assumption is incorrect for granitic rocks.

Magnetite. In granitic rocks all Fe^{3+} usually goes into this mineral in the CIPW norm; but biotite can contain Fe^{3+}.

These differences from the mode are unimportant if the CIPW norm is used solely for comparative purposes. If, however, the norm is to provide a basis for plotting in the systems Q–Ab–Or and An–Ab–Or, then modifications should be made in order to give a norm that is defined, as far as is practicable, in the same terms as the experimental systems.

Methods of modifying the CIPW norm

From the above potential sources of error present in phase diagrams depicting CIPW norm data, the correction technique should account for the presence of micas replacing Hy and Di (rarely present) in granites, and some general rule regarding the status of Il and Mt be formulated. Examples of suitable modifications for a biotite-muscovite granite (the work was carried out using nineteen analysed specimens of the Cairnsmore of Fleet granite mass)[1] are given below and the general implications discussed using data from Tuttle and Bowen (1958).

The most accurate modification involves modal analysis of a rock and chemical analysis of the rock and its individual micas. From the data so obtained precise changes are possible but in certain studies it is desirable, due to the lack of mineral data, to use some simpler and more rapid technique. The latter method was used in the present study.

It was assumed that Il could be removed from the norm calculation and Ti^{4+} be incorporated in Bt in the modified norm. For example, three granites (from the Cairnsmore of Fleet pluton), nos. 31, 125, and 126, contain respectively 9·1, 4·5, and 2·9 % modal biotite, and these biotites contain 3·3, 3·2, and 3·0 % TiO_2; thus TiO_2 present in biotite accounts for 0·30 out of 0·38 %, 0·14 out of 0·17 %, and 0·09 out of 0·15 % total TiO_2 in the respective rocks.

A similar data check of the probable Fe^{3+} distribution was attempted; in this case it was found that some Fe^{3+} was in the biotite but not enough to account for all the Fe^{3+} in the rock. Thus, without accurate mineral analyses of all the granite specimens, it was decided Mt should remain in the modified norm as a standard mineral. The potential discrepancy due to Mt in the norm was estimated as accounting for less than 0·4 % of the Or in the norm.

If biotite is the sole mafic mineral present in the granite, two methods of modification, based on an average biotite formula, may be used. One method is to estimate the modal content of biotite in the rock and the other is to use all Ti^{4+}, Mg^{2+}, and Fe^{2+} (after calculating Mt) for calculating the amount of normative biotite present. Since the second method obviates the necessity for a modal analysis it was employed in the present study, using the average formula $K_2(Ti,Mg,Fe^{2+})_6(Si_6Al_2O_{20})(OH,F)_4$. If the modal technique is used, any chlorite present is classed as biotite. The Bt step was introduced after Mt, before the felsic minerals, and replacing Il and Hy.

Muscovite, when present, cannot be accounted for in this manner since it contains

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[1] The details of the CIPW and modified norms, in the form of a table, are available from the author.

the same ions as Or except for OH^-, which would not form a sound basis for modification purposes. Chemical analysis of muscovite is likewise of no help and one is therefore forced to use modal data. Modal analysis for micas is both simple and rapid (Parslow, 1964, 1966) and it is then an easy matter to apply a new rule using the average formula $K_2Al_4(Si_6Al_2O_{20})(OH,F)_4$. One may note here that modal muscovite mentioned above infers the percentage of primary muscovite only.

From the foregoing discussion it can be appreciated that theoretically an accurate modal analysis should be capable of replacing a normative calculation. However, in practice modal techniques only give percentages of plagioclase and potash feldspar and not of the pure end-members, An, Ab, and Or. This problem is further complicated in granites by the presence of fabrics such as myrmekite and perthite. Modal problems such as these are virtually insoluble, thus the simple normative modification described above is to be preferred.

The importance of the modification can be discussed in terms of its effect on normative felsic constituents and its resultant effect on phase diagrams. The following points of interest are observed when comparing the CIPW and modified norms of the nineteen analysed specimens of Cairnsmore of Fleet granite (see p. 264, n. 1):

The modified norm contains similar excesses (and one small deficiency) of some elements (Al^{3+} and H^-) as does the CIPW norm. These are to be expected since average formulae for biotite and muscovite are used in the corrections and it would be extremely unlikely for the formulae to be perfectly correct. However, these excesses are always smaller in the modified norm than the CIPW norm.

The only two minerals affected by the modification are Or (−4·1 % average) due to K^+ in the micas, and Q (+1·3 % average), due to the differences in the distribution of the silicate groupings in the modified norm.

Summing of the felsic components to 100 % can be considered theoretically and practically. In the case of the Or–Ab–An summation Or is the only molecule to be modified and therefore, since the Ab:An ratio is unchanged, the vector linking the CIPW to the modified norm result must of necessity run through the Or apex. In practice this vector while running through the Or apex is roughly parallel to lines of constant An due to the very small amount of this molecule in granitic rocks. For the Cairnsmore of Fleet specimens, this vector has the average magnitude −3·9 % Or, +3·5 % Ab, and +0·4 % An to account for change from CIPW to modified norm.

The vector direction is more difficult to define in the system Q–Or–Ab since, in addition to the modifications of Or, the Q content is affected due to the change in lattice groupings caused by the presence of micas in the modified norm. In general the vector direction will be inclined towards the Q apex (the amount of this inclination will be proportional to the percentage of mica present) and will not therefore run through the Or apex. In practice, due to the similar proportions of Q, Or, and Ab in granites, this effect is small and the resultant vector is almost at right angles to lines of constant Or. The Cairnsmore of Fleet specimens show an average change from CIPW to mesonorm of +2·6 % Q, −3·8 % Or, and +1·2 % Ab.

The three-component CIPW and modified norms are presented graphically on fig. 1 and their relationships to the thermal troughs and minima at various water

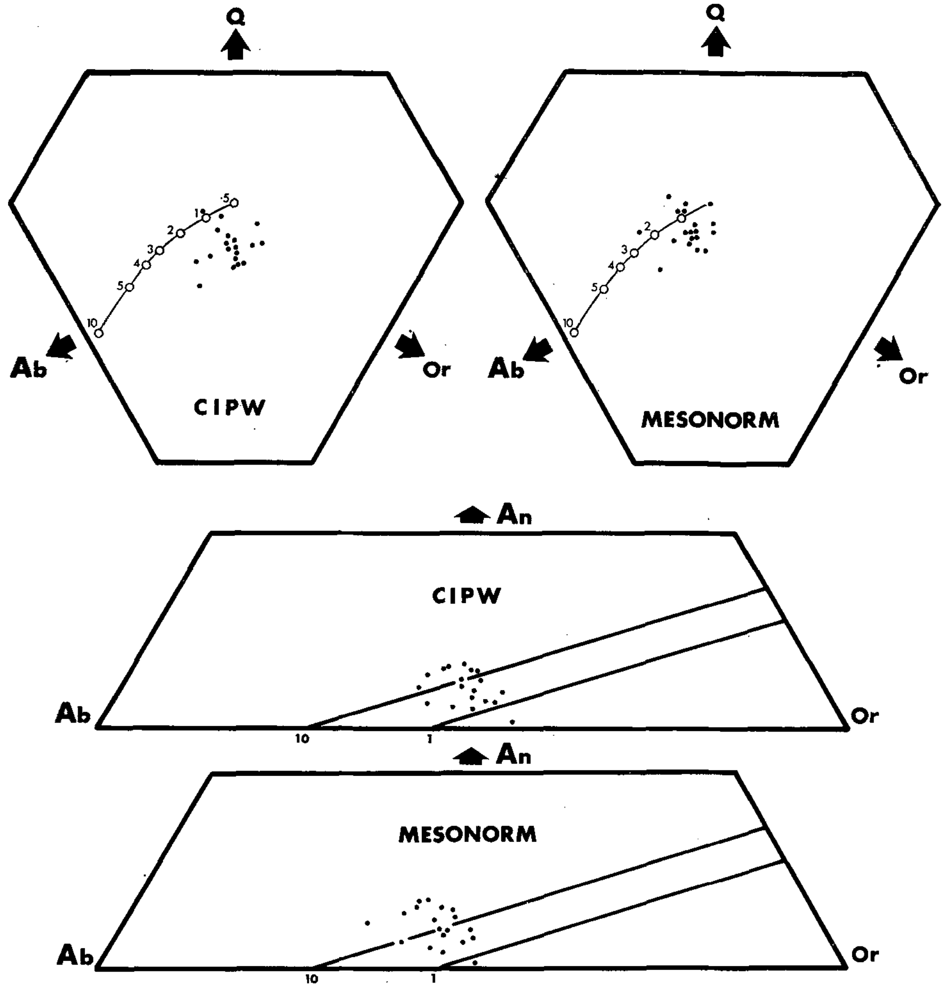

FIG. 1. Comparison of the Cairnsmore of Fleet analyses in the form of CIPW and mesonorms. In the partial Ab–Or–Q diagrams (top) the long sides define 60 % Ab, Or, and Q and the short sides 0 % Ab, Or, and Q. The numbered circles represent the positions of the ternary minimum from 0·5 to 10 kb water vapour pressure. (0·5 kb circle on mesonorm diagram omitted for clarity.) The line linking these points defines the trend of the minima; the thermal troughs containing these minima are not shown but run through these points parallel to the base of the diagrams. In the partial An–Ab–Or diagrams (bottom) the top boundary is 30 % An. The numbered lines represent approximate limits of the thermal troughs between 1 and 10 kb water vapour pressure.

pressures indicated. The arrangement of the vectors is shown in fig. 2*a* by means of average three-component granite compositions of the Cairnsmore of Fleet granite for the two diagrams. From fig. 2, it can be seen that the Q–Or–Ab correction moves a point nearer to the trend of the minima and the direction of movement represents the shortest distance between a CIPW plot and the position of the minima. Thus the

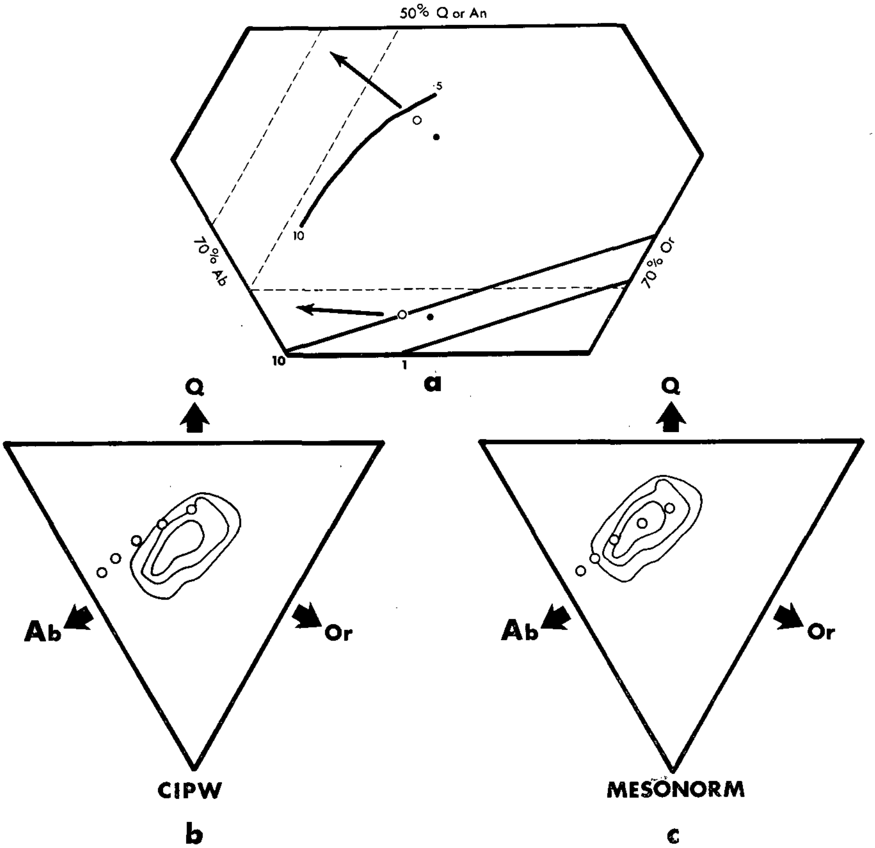

FIG. 2. (*a*) The diagram combines the systems Ab–Or–Q and An–Ab–Or; thick lines define 0 % Q or An, Or, Ab; thin lines define 50 % Q or An and 70 % Ab and Or; dotted lines define equal Or and Q or An contents. Arrows indicate the vector directions produced by the average Cairnsmore of Fleet CIPW norm (●) and mesonorm (○). (*b*) Contour diagram (at 4, 5, and 6–7 %) of CIPW Ab, Or, and Q molecules of 571 plutonic rocks from Washington's Tables (Tuttle and Bowen, 1958, fig. 42) and its relationship to the minima (○) from 0·5 to 4 kb. The boundaries of the diagram are 50 % Q, Ab, and Or. (*c*) Data from (*b*) corrected to approximate to the mesonorm.

modification will have an important bearing on the relationship of a given analysis to the minima. On the other hand, the Or–Ab–An modification runs more nearly parallel to the estimated thermal trough and therefore any modification must be large before any dramatic change in the position of any data relative to the trough occurs.

These directions due to the new rules can now be considered relative to the work of Tuttle and Bowen (1958) and Kleeman (1965). The former (p. 80) have stated: 'In summary, the compositional variations of the analysed rocks with 80 per cent or more albite+orthoclase+quartz are so closely related to the thermal valley on the liquidus surface in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2 that there is little doubt that crystal liquid equilibria are involved in the origin of the bulk of the granites.' This refers to the much-quoted plot of 571 plutonic granitic rocks from Washington's tables (Washington, 1917), which is reproduced in fig. 2*b*. The assumption has been made that the average resultant change for the Cairnsmore of Fleet rocks can be applied to this group and the results are given in fig. 2*c*. Obviously this assumption can be said to be tenuous but nevertheless the result is of great interest for no longer is the maximum 'closely related to the thermal valley' but instead the maximum lies *in* the lowest part of the thermal valley and parallel to the trend of the minima.

Kleeman (1965) concluded that the use of the Or–Ab–An diagram is superior to the aforementioned diagram in petrogenetic studies of granite masses. The data he used show a closer correlation with the thermal trough when An is present than when plotted on the Q–Or–Ab system and any movement away from the trough is into the plagioclase field and links up with the end-points of certain well-defined fractional crystallization trends of basic magmas. While in full agreement with these conclusions, it is considered the above modifications provide a possible explanation as to why this should be so. Due to the vector direction being more nearly parallel to the thermal trough, the system Or–Ab–An is not so susceptible to the effects of the omission of micas from the CIPW norm. The Cairnsmore of Fleet results indicate the change is slightly into the plagioclase field and association with the left-hand side (high-pressure side) of the trough. Other evidence from the pluton (Parslow, 1968) indicates the presence of high pressures during intrusion, thus backing up the results of the correction.

Conclusions

The results indicate that micas are the largest potential causes of error in the direct use of CIPW norms to construct Q–Or–Ab and Or–Ab–An diagrams.

Modifications of the type described are found to be most significant in the Q–Or–Ab diagram and less important in the system Or–Ab–An.

It is suggested that a modified norm of the type described be called a mesonorm since Barth first used this term for norms of metamorphic rocks containing biotite and amphibole.

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