# The relationship of the order of crystallization of basalt melts to their classification and to the definition of rock series

E. P. CAMERON AND W. J. FRENCH

Department of Geology, Queen Mary College, London

SUMMARY. Basalt composition is defined as that chemical composition which when crystallized at one atmosphere under standard conditions will yield olivine, clinopyroxene, and plagioclase as the principal silicate phases. This gives six classes of basalt defined by their order of crystallization but only four of these are encountered in rocks: class 1, olivine→clinopyroxene→plagioclase; class 2, olivine→plagioclase→clinopyroxene; class 3, plagioclase→olivine→clinopyroxene; and class 4, plagioclase→clinopyroxene→olivine. Classes 5 and 6 would have clinopyroxene as the first phase. The class can be determined from the rock composition from multivariate discriminant function equations but Si, Mg, Al, and Na provide a more simple diagnosis via discriminant diagrams. Rock series plotted on these diagrams show systematic trends that allow the series themselves to be classified. Each class corresponds with a commonly recognized basalt type and all four classes relate to tectonic setting groups.

IT has been shown that the one-atmosphere experimental melting data for basalts exhibit a clear relationship between the temperatures of crystallization of the main silicate phases and the rock compositions (French, 1971). In this earlier work binary discriminants were given that allow the order of crystallization of certain minerals to be recognized and multivariate regression equations were given that permit crystallization temperatures to be derived from the rock compositions. A more detailed analysis of the data pertaining to basalts has now been made in order to refine the discriminant equations and to reduce the errors in calculated temperatures. We give here the results of the discriminant function analysis. This shows that the 'order of crystallization' class can be defined from the rock composition and that the commonly recognized basalt types have specific orders of crystallization of the main silicate phases. Some elements are found to be good indicators of order of crystallization and these allow the construction of variation diagrams that depict the basalt classes, allow series to be classified, and show that the classes are related to specific tectonic associations.

## Definition and classification of basalt

Since the object of this work was to deal with the recognition of order of crystallization of silicate phases it was appropriate to make the phase assemblage resulting from one-atmosphere melting experiments the sole criterion for the definition of basalt. Most of the data available for this study relate to rocks that precipitate olivine, clinopyroxene, and plagioclase as the main silicate phases. Rocks for which the experimental data give only two of these silicates are rare and it is possible that experimental difficulties precluded the recognition of small amounts of one phase. It is also possible that some of these rocks have compositions outside the compositional range that gives the three minerals and they were therefore excluded from the analysis. Samples giving orthopyroxene and nepheline were also excluded but in practice there is very little information available for these rocks. In short, for present purposes, basalt is defined as

a rock that precipitates olivine, clinopyroxene, and plagioclase in experiments carried out at one atmosphere. No restriction is placed on the oxygen fugacity or any other compositional variable, but as discussed later it is believed that most of the data used relate to a restricted range of $f_{O_2}$. Rock types normally considered peripheral to basalt such as picrite, hawaiite, mugearite, and basaltic andesite fall within the present definition so that the limits of composition represented by the definition are wide and themselves defined by the available data. It is shown later that rocks falling within the required compositional range can be recognized readily so that the classification can be applied to basalts in the absence of experimental data.
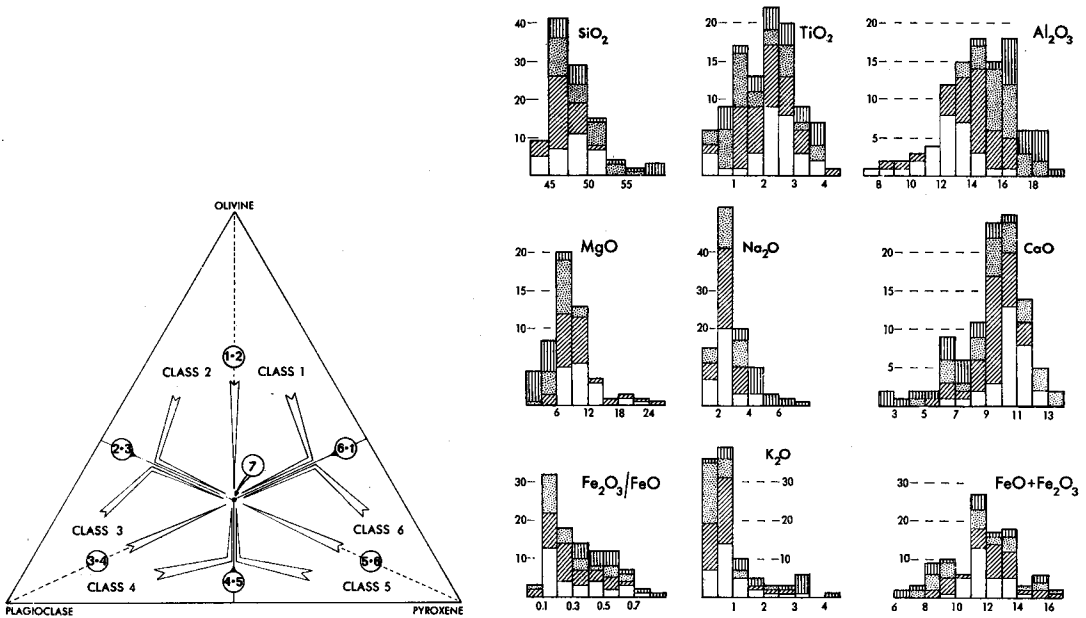


FIGS. 1 and 2: FIG. 1 (left). A diagrammatic representation of the six possible basalt classes based on order of crystallization of olivine, clinopyroxene, and plagioclase. FIG. 2 (right). Frequency distribution of the compositions of the 101 rocks used for the discriminant function analysis. Class 1 basalts are blank, class 2 have diagonal shading, class 3 stippled, and class 4 vertical shading.

From this definition of basalt it follows that six different types may be distinguished by order of crystallization of the three silicates. These can be illustrated in the pseudo-phase diagram given in figure 1, and are referred to as basalt classes[1] 1 to 6. The boundaries are labelled according to the adjacent classes so that 1.2 is the division between classes 1 and 2. Three of the six possible boundaries (1.2, 3.4, and 5.6) represent simultaneous crystallization of the second and third phases and the other three (2.3, 4.5, and 6.1) correspond with co-crystallization of the first two minerals on the pseudo-phase boundaries. The last possible combination has all three minerals crystallizing simultaneously at the pseudo-ternary point and this is labelled 7. Since most of the basalts did not themselves form from residual liquids generated at one atmosphere there is no requirement that they should correspond with the pseudo-boundaries and in practice relatively few rocks approach these lines even if an 'error' zone of

[1] The term 'class' is used to avoid confusion with other groupings already in the literature such as the various basalt types of Kuno (1966), the series of Miyashiro (1975), and the tectonic setting groups of Pearce and Cann (1971) and Pearce (1976).

several degrees centigrade is used in establishing the phase temperatures. These boundaries are therefore considered as the limitations of the areas that are the main types of basalt.

With the first collection of data for the discriminant analysis it became clear that clinopyroxene is hardly ever the first mineral to crystallize from basaltic melts at one atmosphere and hence that only four classes need be considered. These are:

class 1, olivine →clinopyroxene →plagioclase; class 2, olivine →plagioclase →clinopyroxene; class 3, plagioclase →olivine →clinopyroxene; and class 4, plagioclase →clinopyroxene →olivine.

The reason for the absence of classes 5 and 6 is that most basalts represent residual liquids derived at high pressure and that at high pressure the minimum-melting compositions are normatively plagioclase-rich or olivine-rich relative to the corresponding one-atmosphere compositions (O'Hara, 1968; Clarke, 1970). Only if the magma rises extremely slowly would it be possible for the liquids to approach the low-pressure minimum-melting composition. Further, if mantle compositions are modelled as pyrolite or any other kind of peridotite, partial melting will provide melts on the olivine-rich side of the low-pressure minimum and a special evolutionary history is required to yield melts precipitating plagioclase as the first mineral at one atmosphere if the melts were initially derived by partial melting of pyrolite.

### Chemical and experimental data and errors

The data used for the present work have been taken from various sources (Table I). A total of 101 rocks was used and the frequency distributions of the oxides of these rocks are illustrated in fig. 2. These compare well with the distributions given by Chayes (1965) for oceanic and continental margin volcanics, but it appears that the present data are biased towards oceanic basalts. This is shown most clearly by the $TiO_2$ frequency distribution, which is bimodal with the two peaks corresponding with continental and oceanic compositions. The present distribution of $TiO_2$ suggests that oceanic basalts are over-represented in the basalts for which experimental data are available.[1]

Misclassification of basalt can of course arise in the original data from both chemical and experimental sources. Errors in chemical analysis are well known from the work on Gl and Wl and other standard rocks but there is no equivalent standard for the experimental data for basalts, a deficiency that should perhaps be remedied. Possible errors spring from numerous sources. It is necessary, for example, to have sufficient of a phase developed or remaining for it to be identified and for grains to be large enough for correct visual identification. The charges are prepared in various ways and it is difficult to be sure of the precise conditions obtaining in sealed capsules especially where the charges contain various amounts of volatiles. Some of the data used here were obtained from experiments buffered with respect to oxygen and this variation in oxygen fugacity will cause some variation in phase temperatures. However, in runs of relatively short duration in closed capsules, the oxygen fugacity will be buffered by the iron–oxide ratio of the rock. Experiments suggest a typical value of $10^{-7}$ atmospheres (Fudali, 1965), while runs in open capsules will have an oxygen fugacity approaching 0·2 atmospheres.

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[1] In general the distributions are not normal and this may have important consequences for the application of the statistical techniques. No one systematic transform can convert all the frequency distributions into the normal form and though it might have been possible to convert each separately this would have introduced unwarranted and uncontrollable weighting of the oxide abundances. We are conscious of the dangers of using discriminant function techniques on data that are not normally distributed. However, Lachenbruch, Lilienthal, and Revo (1969) have concluded from a study of the effects of certain types of non-normality that the only satisfactory test of the robustness of the discriminant technique is the degree of misclassification produced in applying the equations to the data from which they were derived. The results obtained indicate that the treatment is justified in the present application.

<center>TABLE I</center>

| Source | Sample numbers | Notes on experimental techniques |
| --- | --- | --- |
| Yoder and Tilley, 1962 | Table 2, Nos.5,7,20 | Environment–air, sealed Pt capsule or $N_2$ and Pt or Fe crucible.Temperature of phase disappearance determined |
| Tilley, Yoder and Schairer, 1964 | Table 1, Nos.MK,HK. | As for Yoder and Tilley, 1962. |
| Tilley, Yoder and Schairer, 1965 | Table 1, Nos.KIg, 1921–F, 1920–PH, Table 2, Nos.Ha,X,6,$T_{114}$, Table 3, Nos.$T_{364}$, 1801,(2), 1921–PH, 1921–T, Ac, mb, bm,(3) | As for Yoder and Tilley, 1962. |
| Tilley, Yoder and Schairer, 1966 | Table 4, Nos.1.2,5 Table 5, Nos.1,2,3 Table 6, Nos.$D_{cp}$,$D_{cg}$,(111), (97),(95),(15). | As for Yoder and Tilley, 1962. |
| Brown and Schairer, 1967 | Table 19, Nos.3S,5S,7S,9S,24V | As for Yoder and Tilley, 1962. |
| Tilley, Yoder and Schairer, 1967 | Table 17, Nos.1,3 | As for Yoder and Tilley, 1962 |
| Thompson and Tilley, 1969 | Table 1, Nos.1959A,1959B, 1960–1,F14,M1 | Environment–sealed Pt capsules in air. Temperatures of phase appearance determined |
| Tilley and Thompson, 1970 | Tables 1,2,3,4 and 6 Nos.65,63,62,64,64g,k,b,d, 70,68,OB32,CP40,CM3,CM2, Ska,8048,6160 | As for Tilley, Thompson and Lovenbury, 1972 |
| Thompson and Flower, 1971 | AJ68,AJ33,AJ102,AJ123 | As for Tilley, Thompson and Lovenbury, 1972 |
| Tilley, Thompson, Wadsworth and Upton, 1971 | RE114,RE168,RE331,RE343 RE171,RE134,RE69,RE332 | As for Tilley, Thompson and Lovenbury, 1972 |
| Tilley, Thompson and Lovenbury, 1972 | Table 1, Nos.T89,T96,4519/11, 4519/4519/34,4519/45,4519/65 St7,6231,6231,6243,2,EG7040, Pal 70,6244 | Environment – 1230°C argon – 1230°C air – 1150°C $Ag_{70}Pd_{30}$ capsule – 1150°C Pt capsule Equilibration time, 1 hour or longer for low temperature runs. Temperature of phase appearance determined. |
| Thompson, Esson and Dunham, 1972 | Table 1, Nos.908,894,286 961,970,939,981,270,931,986 Table 4, Nos.983,946 | Environment – 1300°C open in argon – 1300°C sealed in air – 1160°C $Ag_{70}Pd_{30}$ capsule – 1160°C Pt capsule Equilibration time, 1 hour. |

The experiments of Hill and Roeder (1974) show that olivine and plagioclase temperatures are changed by only a few degrees over this range but that clinopyroxene temperatures are more strongly affected. Hence the order of crystallization may be influenced by the oxygen fugacity with the order of the second and third phases most seriously affected. In most experiments the recorded temperatures are determined by interpolation between bracketing runs some 20 °C apart and it is not always clear that the temperature of crystallization has been approached from both above and below. It therefore seems likely that the error in recorded

temperature will be considerably greater than that found in calibrating the furnace and may approach several degrees. Errors due to chemical analysis may therefore be small in comparison with the experimental error in temperature when each error is expressed in terms of the range of composition or range of temperature. Nevertheless the boundaries between classes of basalt will be blurred by both analytical and experimental errors as well as from imperfections in the discriminant function analysis.

### Multivariate discriminant function analysis

It is common to use normative calculations to construct pseudo-phase diagrams displaying crystallization history and we have calculated various normative tetrahedra like that of O'Hara (1965) for the available basalt data. Overlap of order of crystallization volumes in the vicinity of the pseudo-phase boundaries is considerable and this means that the planes must be defined statistically. The calculations of course also take no account of certain major elements. However, the normative approach is not essential to the calculation of orders of crystallization, for the norms are essentially linearly related to the rock chemistry: the Mg, Ca, Al, Si tetrahedron, for example, contains the subordinate tetrahedron ab, an, di, fo.

Discriminant function analysis was therefore performed on the chemical analyses and phase data taking the oxides in various combinations from binaries up to twelve-oxide functions including $H_2O+$. Details of the mathematics of the procedure have been given by Anderson (1958) and a suitable computer program was available (Dixon, 1973). The best classification was, as expected, found for the largest number of oxides and the function coefficients and constants obtained by the analysis are as follows where $F_i$ is the discriminant function for class i.

$$F_1 = 70{\cdot}51626SiO_2 + 107{\cdot}90992TiO_2 + 71{\cdot}96936Al_2O_3 + 57{\cdot}26419Fe_2O_3 + 22{\cdot}07212FeO +$$
$$308{\cdot}93168MnO + 63{\cdot}38610MgO + 47{\cdot}72285CaO + 20{\cdot}24445Na_2O + 2{\cdot}62142K_2O +$$
$$68{\cdot}36266H_2O + + 220{\cdot}16209P_2O_5 - 3135{\cdot}33575$$

$$F_2 = 70{\cdot}22053SiO_2 + 107{\cdot}09320TiO_2 + 73{\cdot}44313Al_2O_3 + 57{\cdot}70120Fe_2O_3 + 22{\cdot}25869FeO +$$
$$316{\cdot}74333MnO + 63{\cdot}58940MgO + 46{\cdot}80725CaO + 19{\cdot}87252Na_2O + 1{\cdot}11991K_2O +$$
$$68{\cdot}28528H_2O + + 223{\cdot}84279P_2O_5 - 3135{\cdot}69883$$

$$F_3 = 70{\cdot}50179SiO_2 + 107{\cdot}28410TiO_2 + 73{\cdot}98163Al_2O_3 + 57{\cdot}80774Fe_2O_3 + 22{\cdot}08177FeO +$$
$$336{\cdot}65572MnO + 63{\cdot}49836MgO + 46{\cdot}99174CaO + 19{\cdot}93854Na_2O + 0{\cdot}63254K_2O +$$
$$69{\cdot}46023H_2O + + 223{\cdot}72020P_2O_5 - 3162{\cdot}01547$$

$$F_4 = 70{\cdot}45514SiO_2 + 108{\cdot}84366TiO_2 + 74{\cdot}65239Al_2O_3 + 58{\cdot}09769Fe_2O_3 + 21{\cdot}86512FeO +$$
$$335{\cdot}00565MnO + 63{\cdot}67360MgO + 46{\cdot}13902CaO + 20{\cdot}70268Na_2O + 2{\cdot}20898K_2O +$$
$$69{\cdot}01089H_2O + + 220{\cdot}02327P_2O_5 - 3170{\cdot}05328$$

If values of $F_1$, $F_2$, $F_3$, and $F_4$ are calculated for a given rock then the highest F value indicates the most likely basalt class. The probability of the rock belonging to each of the four classes can then be found from

$$P_i = e^{(F_i - F_i(max))} / \Sigma e^{(F_i - F_i(max))}$$

where $P_i$ is the probability of the rock belonging to class 'i'. Probabilities have been calculated for all the standard rocks and the class decided from the highest probability. For class 1 basalts 5 out of 29 are misclassified but 4 of these are placed in the neighbouring class 2. These therefore differ only in the uncertainty as to whether plagioclase or pyroxene is the second phase

to appear. The fifth misclassification gives probabilities of 0·088 for class 1 and 0·057 for class 2 and must be considered a serious error in the chemistry, the experimental data, or the calculations. Of the 31 class 2 basalts only 6 are misclassified and of these 5 are allocated to neighbouring classes, 4 to class 1 and 1 to class 3. The sixth rock gives very low probabilities for all four classes and must be considered a poorly defined rock intermediate in its affinities. Class 3 basalts are the least well characterized and there are 9 misplacements out of the 25 samples. Of these, 7 are allocated to adjacent classes but for 3 samples the probability of the
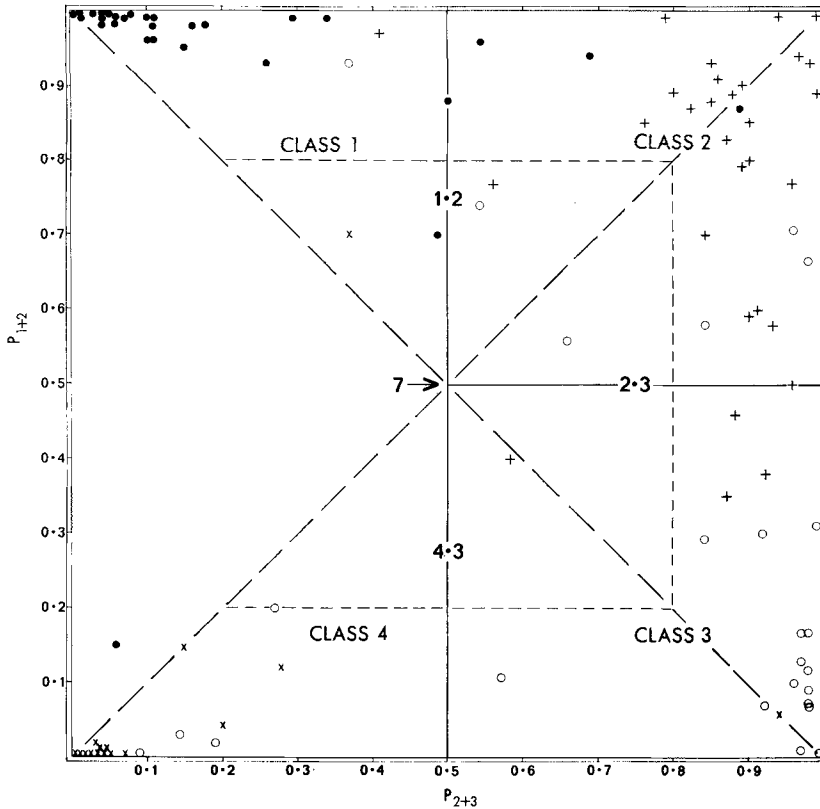


FIG. 3. A plot of the summed probabilities of each rock belonging to classes 1 and 2 ($P_{1+2}$) and classes 2 and 3 ($P_{2+3}$). Some of the points for classes 1 and 4 should be closer to the corners of the diagram but have been spread to clarify the plot. Circles are class 3, filled circles class 1, vertical crosses class 2, and diagonal crosses class 4.

incorrect classification is more than 0·8. It therefore seems that this class is poorly defined by the compositional and experimental data. This contrasts with class 4 for here, although there are only 16 samples, 14 are correctly classified with a very high degree of probability, and the other two are placed with neighbouring classes. The qualities of the classification can be displayed diagrammatically by plotting the sum of the probabilities for classes 1 and 2 against the sum of the probabilities for classes 2 and 3 (fig. 3). This diagram makes clear the strong contrasts between classes 1 and 4 and shows the greater mergence between classes 1 and 2, 2 and 3, and 3 and 4. Six points are allocated to particular groups with summed probabilities of less than 0·8 and these may possibly be interpreted as intermediate types close to the pseudo-ternary composition. This diagram can also be used as a variation diagram permitting comparison to

be made between provinces. However, the plot is not easy to interpret in terms of the mechanisms creating the class differences because of the complexity of the numerical treatment of the rock chemistry.

*Binary and ternary discriminants*

If, as magma rose through the lithospere, equilibrium was established continually between solids and residual melt, then the final residual liquid would correspond with the pseudo-ternary point represented by point 7 on fig. 1. Departure of a rock composition from this point is therefore a measure of the departure from the path of continual equilibrium differentiation on rising to the surface. Classification into the present groups should therefore reflect the conditions through which the melt has passed and the mechanisms that have controlled the generation of the erupted compositions. The four classes should represent genetically related rock suites with common patterns of differentiation. The difficulty of interpreting fig. 3 from this point of view has already been mentioned. Fig. 2, however, shows that certain oxides are specially useful in defining the rock class. MgO and $Al_2O_3$ are the most significant as would be expected from the fact that they represent the abundance of olivine and plagioclase respectively. $Na_2O$, $SiO_2$, and CaO are somewhat less meaningful but still provide useful information, and plots of pairs of these oxides and of total alkalies against silica are given in fig. 4. Some of these plots have considerable discriminant value but they also show that the classification of basalt types given by Kuno (1966) does not always correspond with the present grouping. The MgO against $Al_2O_3$ diagram is most useful in permitting the separation of the four classes, and equations are given to the binary linear discriminant curves in the figure. Similarly $Na_2O$ against $Al_2O_3$ allows a separation to be made between classes 3 and 4.

Because temperature of crystallization is related to the mole-fraction of particular elements, a ternary diagram for discriminant purposes should be three-dimensional. Plotting oxides such as $MgO-SiO_2-Al_2O_3$ in this way using a visual display linked to the computer shows good discriminant qualities but the diagram is difficult to present and to use in two dimensions. The ternary diagrams are therefore presented in the rather less efficient but more familiar triangular diagrams. The triangles Si–Al–Mg and $MgO-Al_2O_3-0\cdot5Na_2O$ depict the four classes satisfactorily and are given in figs. 5a and 5b. The class boundaries are plotted and boundary equations are given in these figures, the boundaries being drawn visually as the best straight lines. By plotting on the Si–Al–Mg triangle the probability of each rock belonging to a particular class obtained from the multivariate analysis, it is possible to show the areas corresponding with particular levels of probability. For the purpose of plotting, the levels of probability are abbreviated to whole numbers from 0 to 9 where the number is the first digit of the actual probability value. The diagrams obtained in this way are given as figs. 5c, d, e, and f. The areas corresponding with particular classes are sharply defined and in each diagram areas of high probability give way to areas of low and usually zero probability. These figures may therefore provide a useful means of estimating the class of a particular basalt. The probability values used derive from the multivariate analysis and do not relate specifically to the Si–Al–Mg proportions but the correspondence of the areas of high probability with the class boundaries marked in fig. 5a shows the high discriminant value of the triangular diagram.

As Le Maitre (1976) has pointed out, a difficulty in using discriminant analysis is that the system fails to recognize when a rock does not belong to any of the defined groups. For present purposes this means that a separate system must be found for recognizing that the rock will precipitate the three silicates. Figs. 2, 3, 4, and 5 probably provide such a system and, for the multivariate equations to be applicable, the chemical analysis should fall within the range of the compositions used to construct the equations. Experiments have been made on a series of
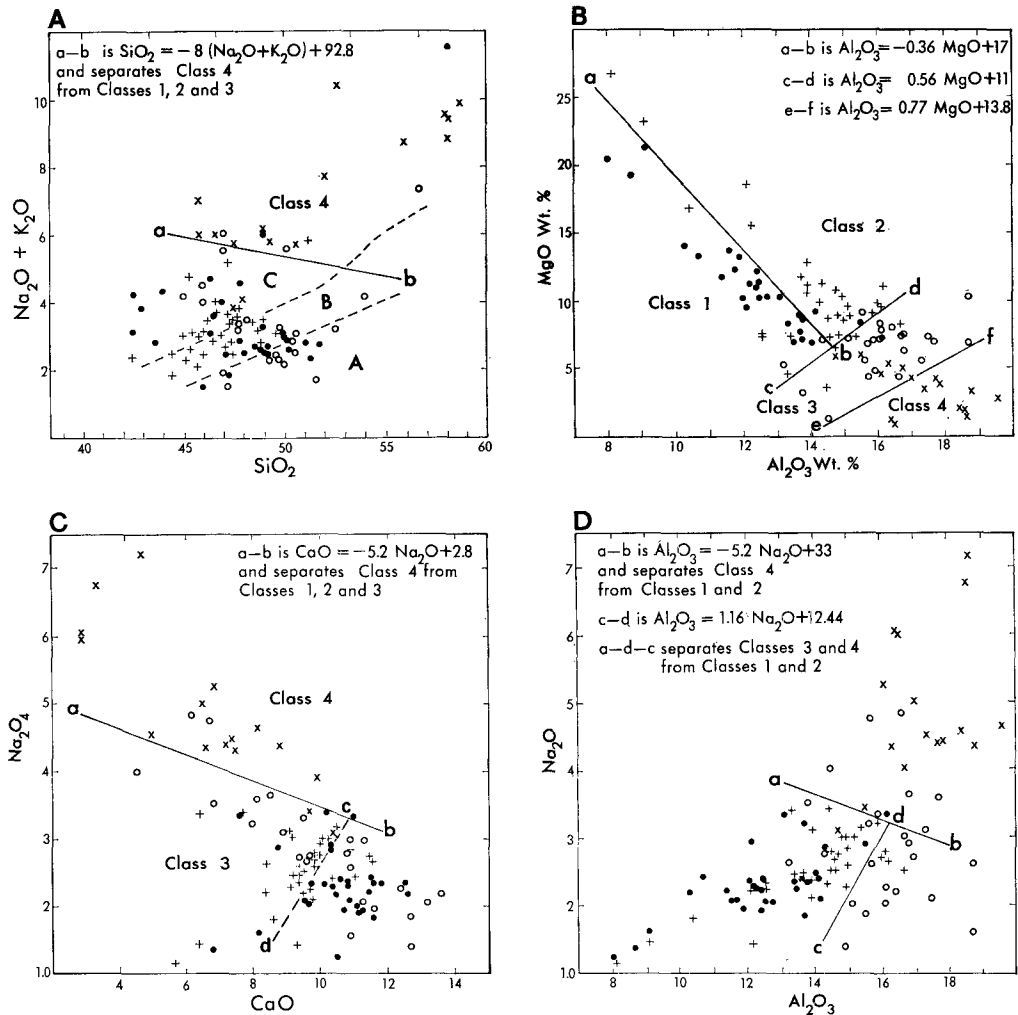
FIG. 4. Some binary discriminant diagrams for the four classes of basalt. Circles are class 3, filled circles class 1, vertical crosses class 2, and diagonal crosses class 4. The broken lines on fig. 4a are from Kuno (1966).

rocks from Ua Pu (Marquesas Islands), the compositions of which straddle the outer boundary of the present data. The results of these experiments show that limited extrapolation leads to little loss in the quality of the estimate of the order of crystallization. Nevertheless, extrapolation is not acceptable and further data are required to fix the outer limits of basalt composition as defined for this work. Evidently the probability of a given rock falling within the present range can be obtained by a calculation of the kind advocated by Le Maitre (*op. cit.*). If a basalt *can* be identified as falling within the wide range of compositions of the present experimental data its class can be determined from the multivariate formulae. Its distinctiveness can then be judged from the calculated probability values or from the position of the rock when it is plotted on the binary or ternary diagrams of figs. 4 and 5.

Examination of a large number of basalt analyses, including those that have been the subjects of experiments, shows that the class 1 basalts are essentially tholeiites and olivine tholeiites
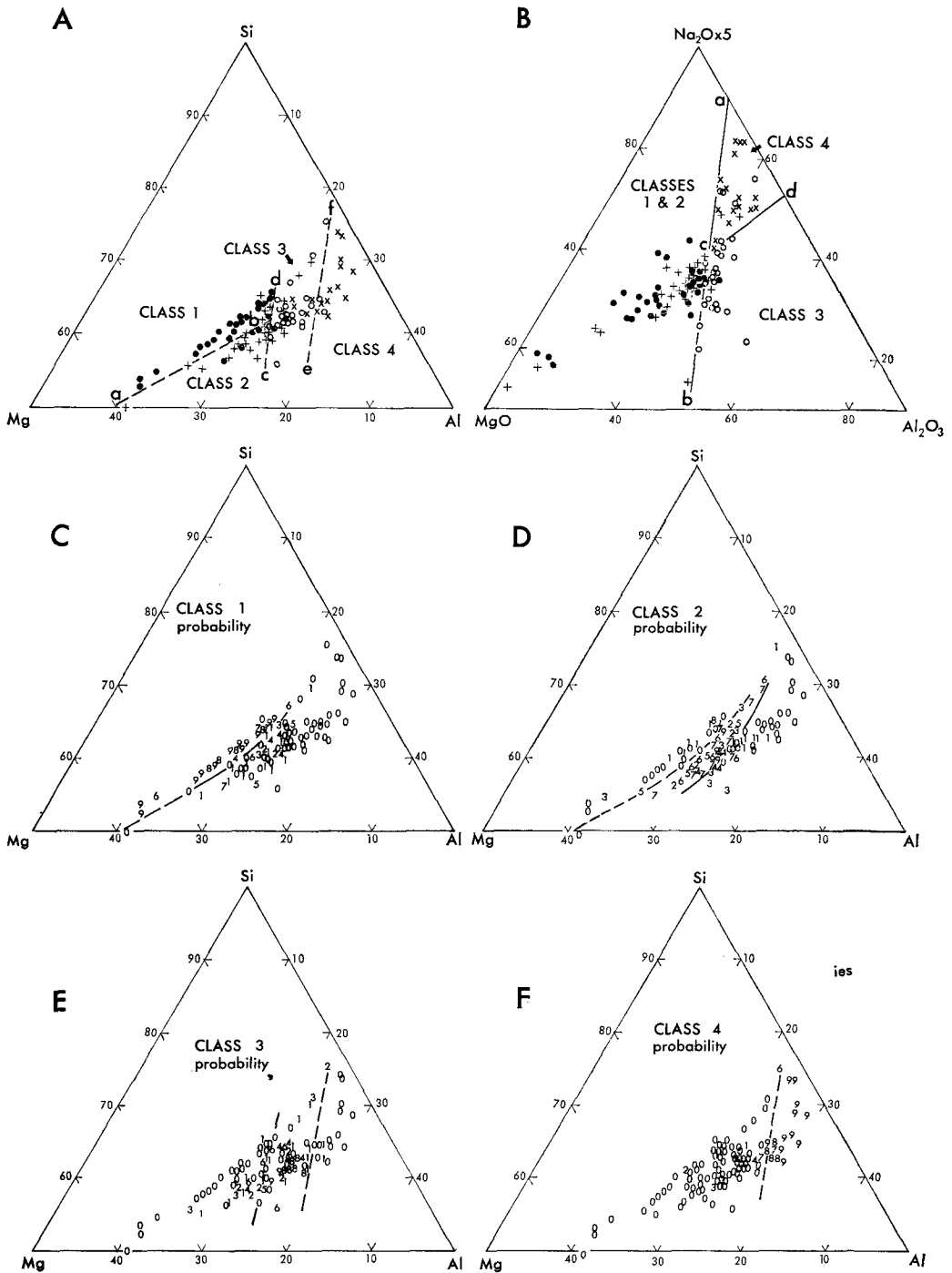
FIG. 5. a, Si–Al–Mg diagram with discriminant boundaries as follows: ab is $Al = -0.52Mg + 30.5$; cd is $Al = 0.65Mg + 12.2$; and ef is $Al = 0.59Mg + 21.0$. b, $MgO-Al_2O_3-5Na_2O$ discriminant diagram, ab is $Al_2O_3 = -0.40Na_2O^* + 57.0$, cd is $Al_2O_3 = 0.61Na_2O^* + 15.0$. ($Na_2O^* = 500Na_2O)/(5Na_2O + MgO + Al_2O_3)$). The symbols used here are as for fig. 4. C, D, E, and F, multivariate probability for each rock for each class plotted on the Si–Al–Mg triangle. The number plotted is the first digit of the actual probability.

and class 2 are alkali-olivine basalts. Class 3 rocks have been given various names but are dominated by high-alumina basalts with some extreme tholeiites and basaltic andesites. It may be reasonable to divide class 3 on the Si–Al–Mg diagram by extrapolation of the boundary between classes 1 and 2. Two class 3 types may then be defined as high-alumina tholeiite and high-alumina olivine basalt. Class 4 rocks are generally basaltic andesites and include some rocks that might normally be considered to be andesites. They are rarely the dominant rocks of the provinces but tend to be minor associates of provinces dominated by class 2 or class 3. They may perhaps be named basaltic andesite.

### Volcanic groups and variation diagrams

The discriminant diagrams of figs. 4 and 5 are also useful variation diagrams. They allow rock groups to be compared and classified and may be of value in suggesting the mineralogical control vectors of differentiation. Class boundaries and trends shown in fig. 6 indicate that classes 1 and 2 are probably influenced by olivine–liquid equilibria while 3 and 4 appear to relate more closely to either garnet (at high pressure) or olivine and plagioclase crystallization (at low pressure).

Several volcanic series are plotted in fig. 6. It is not intended to discuss the details of individual series here, but certain generalizations can be made. Thus, series dominated by basalts of classes 1 and 2 trend from the compositions of common olivine and pyrolite, but where the series cross into class 3 contrasts arise in the trend lines. Some series continue on straight lines from class 2, through class 3, and even into class 4, while others turn to run in class 3. The straight trends appear to indicate a simple differentiation mechanism involving a single solid phase or more phases in uniform proportions, while the curved trends suggest a change in the phases being precipitated through the evolutionary history. For none of the series studied so far, and this includes all of those given in Carmichael, Turner, and Verhoogen (1974), does the change in trend direction begin until the compositions fall in the area of class 3. This seems to indicate a compositional control on the precipitation of the phases necessary to cause the change in trend such as garnet and feldspar. Calc–alkaline series lie within class 3 though some have basic members of class 2 compositions as well. The Thingmuli series (Carmichael, 1964) also lies wholly within class 3 though here the curvature is opposite to that of the usual calc–alkaline series.

On a broader scale the basalts of particular provinces often fall within particular classes. The Hawaiian basalts are dominantly class 1 but some fall in the low-Mg part of 2. The Karroo, Palisades, and Tasmanian dolerites have compositions falling in the low-Mg part of class 1, while Antarctic, Hebridean, Eastern North American, and Columbian quartz dolerites and plateau basalts are dominantly of low-Mg class 2 compositions. The oceanic crust along the ridge systems is also largely of low-Mg 2 and siliceous 3 types. Island-arc and continental-margin suites are of two kinds, one falling wholly within class 3 while the other has a proportion of class 2 basalts along with the class 3.

These relationships show that the order of crystallization classes echoes the widely recognized volcanic associations and it is possible that the definition of these associations can be made in terms of the classes. If comparison is made with the tectonic setting groups defined by Pearce (1976) (fig. 7), it is seen that the majority of the basalts for which experimental data are available fall in the wide fields of oceanic island and continental basalts. The most obvious property of this plot, however, is that Pearce's $F_1$ and $F_2$ functions allow a sharp division to be made between class 3 basalts and the rest. These class 3 compositions mostly fall in the field labelled calc–alkaline, ocean floor basalt, and low-potassium tholeiites. Not all the basalts used for the present study can, however, be plotted on the figure, for this discriminant diagram is based
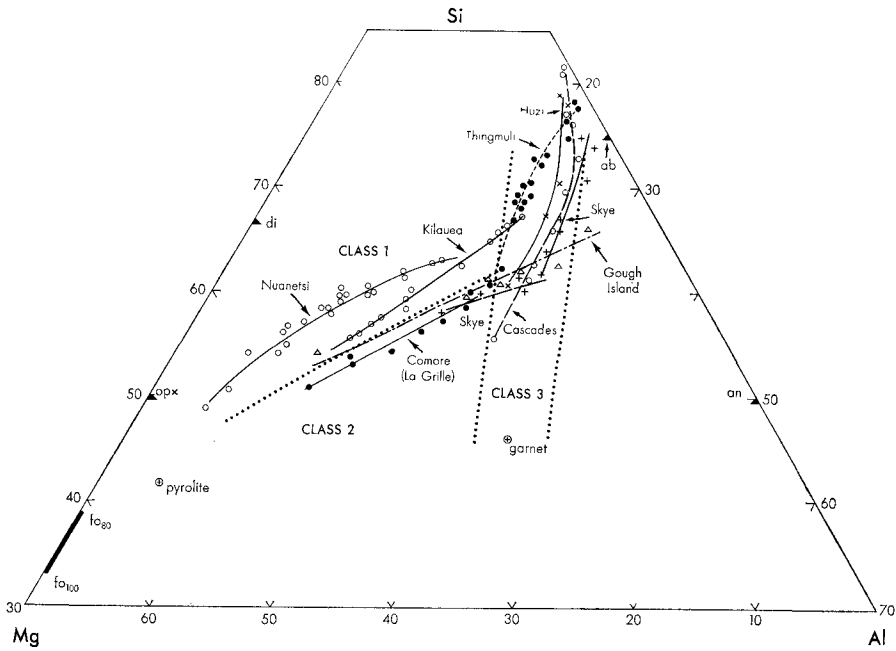
FIG. 6. Some possible rock series plotted on the Si–Al–Mg diagram. The dotted lines are class boundaries from figure 5a. Data from Carmichael (1964), Turner and Verhoogen (1960), Wright and Fiske (1971), Thompson, Esson, and Dunham (1972), Cox and Jamieson (1974), Strong (1972), Tilley, Yoder, and Schairer (1967), Le Maitre (1962), Green and Ringwood (1960), and Ringwood (1975).
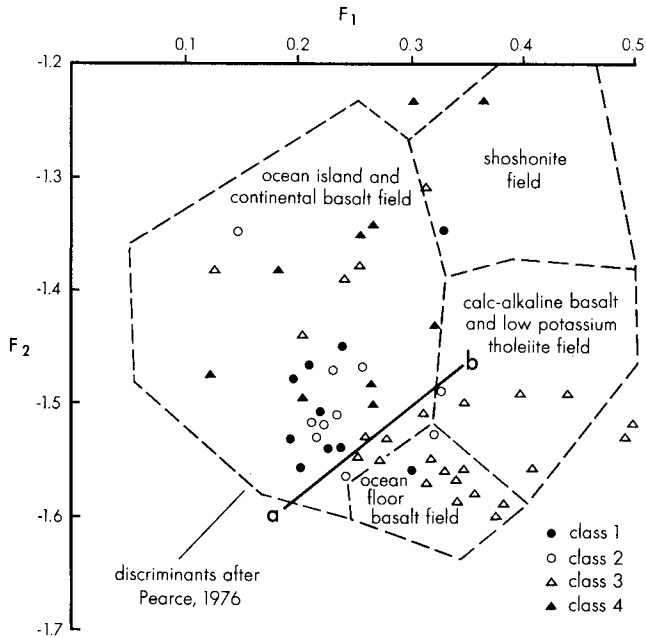


FIG. 7.

on an arbitrarily limited composition range. The shoshonite field is almost empty and there is evidently a need for further data on these rocks. An important difference between the present work and discrimination directly into tectonic associations is that the classification based on order of crystallization requires no prior allocation of the standard data to presumed tectonic groupings. If associations emerge from the present system they do so because they have particular petrogenetic schemes.

It is tempting to make more of the discriminant boundaries than is justified, as is readily seen by drawing outlines of the areas over which particular basalt types fall and noting the overlap between the areas. Examination of fig. 7 shows a large number of points falling in the area labelled oceanic island and continental basalt field but many of these points are misclassified in terms of the tectonic setting. Considerable caution is therefore required in applying the results of the present study: a basalt can be allocated to a class but only with a particular probability of being right. This probability has to be calculated for each sample. On the other hand the definition of classes can be made unambiguously but arbitrarily on the Si–Al–Mg diagram where the discriminants can be used as arbitrary boundaries. It is therefore suggested that the classification can be used at two levels: the multivariate procedure gives the probability of the rock belonging to a particular group while the Si–Al–Mg diagram can be used to make assignments to arbitrary, chemically defined classes corresponding more or less with the order of crystallization classes and with the usually recognized basalt types.

*Conclusions*

Common basalts show four orders of crystallization of the main silicates when crystallized at one atmosphere and this provides a useful means of classification. If experimental data were to be obtained for basalts yielding another phase, such as nepheline, the number of possible classes would be 24. Many such classes would be void, however, and it is likely that extension of the system to include additional phases would be profitable. Rocks can be placed into the classes by means of multivariate discriminant equations and the probability of the correctness of the allocation can be calculated. A closely analogous arbitrary classification can be based on simple variation diagrams such as the Si–Al–Mg diagram. This arbitrary system, if based on the triangles of fig. 5, allows the classes to be defined by the following inequalities: referring to fig. 5a, a sample belongs to class 1 if $Al < 0.65Mg + 12.2$ and $Al < -0.52Mg + 30.5$, class 2 if $Al < 0.65Mg + 12.2$ and $Al > -0.52 + 30.5$, class 3 if $Al > 0.65Mg + 12.2$ and $Al < 0.59$ $Mg + 21.0$, and class 4 if $Al > 0.59Mg + 21.0$. If the triangle $Na_2O^* - MgO - Al_2O_3$ is considered then the rock belongs to classes 1 or 2 if $Al_2O_3 < 0.40Na_2O^* + 57.0$ and to 3 or 4 if $Al_2O_3 > 0.40Na_2O^* + 57.0$. If $Al_2O_3 > 0.61Na_2O^* + 15.0$ the sample belongs to class 3 rather than class 4. The classes can be named according to the main types of basalt occurring in each. Class 1 is then the tholeiite class, class 2 the alkali olivine basalt, class 3 the high-alumina basalt (with subdivision into high-alumina tholeiites and high-alumina olivine basalt), and class 4 basaltic andesite. This classification may allow volcanic series to be defined and compared and distinction to be made between series found in differing tectonic regimes. The boundary between classes 1 and 2 on the one hand and classes 3 and 4 on the other appears to be specially significant and may mark the important chemical differences between the calc-alkaline association and the other volcanic associations and probably reflects the differences between their petrogeneses.

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