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A Guide to the Chemical Classification of the Common Volcanic Rocks

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A system is presented whereby volcanic rocks may be classified chemically as follows:

- I. Subalkaline Rocks:
 - A. Tholeiitic basalt series:
Tholeiitic picrite-basalt; tholeiite; tholeiitic andesite.
 - B. Calc-alkali series:
High-alumina basalt; andesite; dacite; rhyolite.
- II. Alkaline Rocks:
 - A. Alkali olivine basalt series:
 - (1) Alkalic picrite-basalt; ankaramite; alkali basalt; hawaiiite; mugearite; benmorite; trachyte.
 - (2) Alkalic picrite-basalt; ankaramite; alkali basalt; trachybasalt; tristanite; trachyte.
 - B. Nephelinitic, leucitic, and analcitic rocks.
- III. Peralkaline Rocks:
pantellerite, commendite, etc.

Introduction

In 1966, at the request of the Volcanological Subcommittee of the Associate Committee on Geodesy and Geophysics of the National Research Council of Canada, the authors together with Professor W. W. Moorehouse undertook to prepare a classification of volcanic rocks which might be recommended by the subcommittee for general use in Canada. It was felt that such a classification was needed because (a) several institutions in Canada had begun to produce large numbers of chemical analyses of volcanic rocks with the consequent need for meaningful comparisons of these data by means of a consistent nomenclature; (b) many of the rocks being analyzed were metamorphosed to a degree that precluded classification by conventional mineralogical systems; and (c) there was no existing classification that related in a concise quantitative way long-standing terms such as basalt, andesite, and dacite with newer names such as high-alumina basalt and hawaiiite, which were becoming popular in petrological literature. With Professor Moorehouse's untimely death in 1969, the authors continued the project.

A preliminary draft of their report was distributed to interested parties for criticism and comment in the period 1967-1969. The pres-

ent paper constitutes their final report. It has been formally accepted by the Volcanological Subcommittee,¹ which hopes, by its publication, to establish an acceptable and useful classification of volcanic rocks in Canada.

Scope and Approach

The term "common volcanic rocks" is intended to cover those compositional types most frequently encountered, whether unaltered or metamorphosed. Only primary rock names are used here, but modifiers such as a "meta-" prefix may be added if appropriate. The proposed classification scheme (Fig. 1) has two major divisions, the subalkaline and alkaline rocks, and a third, minor category, the peralkaline rocks. However, most of the common volcanic rocks fall into three series within the first two divisions—the tholeiitic basalt series, the alkali olivine basalt series, and the calc-alkali series—and it is on these that we shall concentrate. The peralkaline rocks and the other rocks mentioned in Fig. 1 (the nephelinites, leucitites, and analcites) are given only brief attention, partly because they appear to be rare in Canada, but mostly because they are complex groups outside our experience and

¹Chaired by Dr. A. M. Goodwin.

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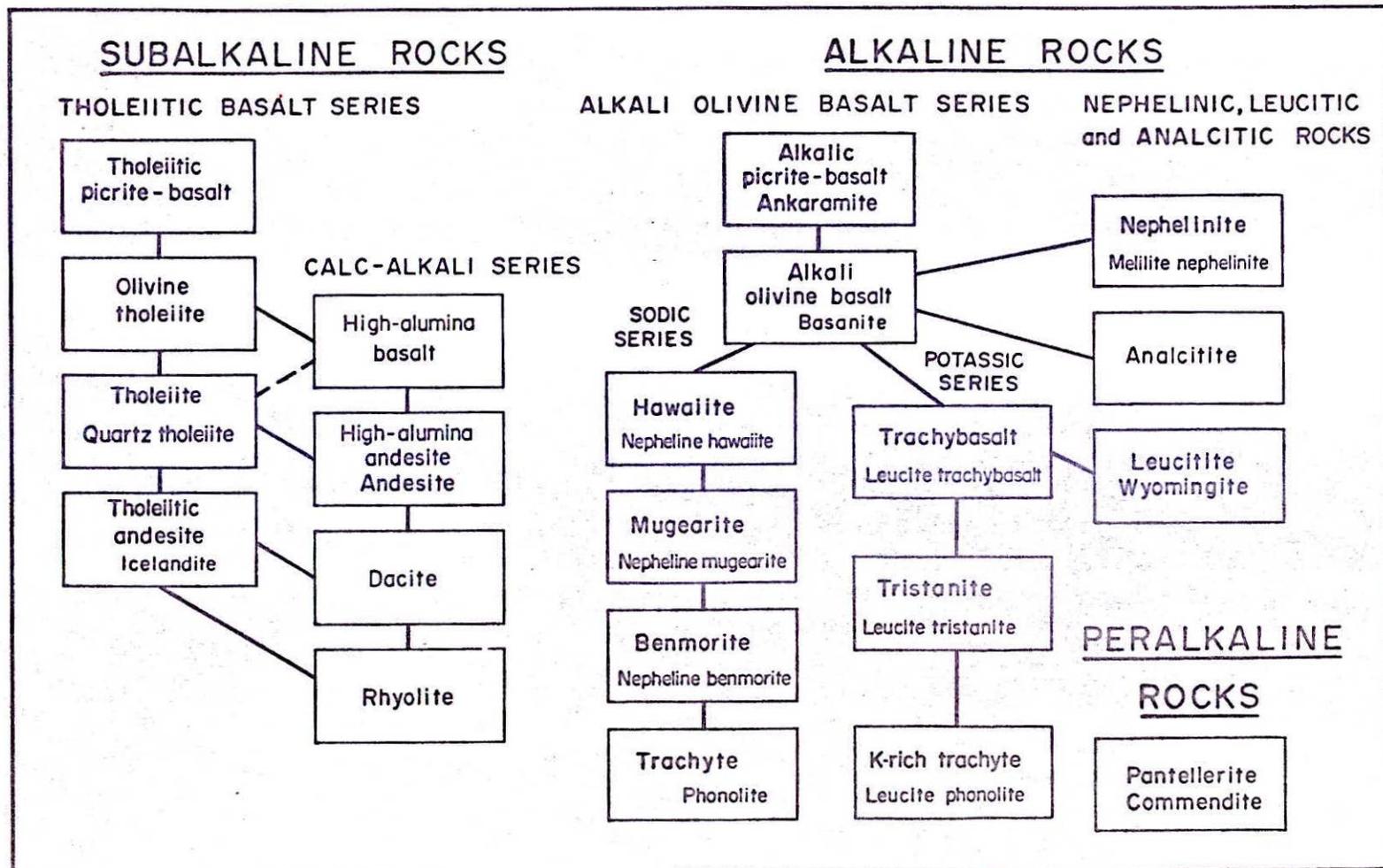


FIG. 1. General classification scheme for the common volcanic rocks. The lines joining boxes serve to outline common associations. The rocks indicated by small print within the boxes are variants of the main rock.

any comments we might make might be more misleading than helpful. For these same reasons we have avoided the spilites.²

The essential aim of the classification is to give chemical definition to conventional rock names, these generally having been originally defined on a mineralogical basis. However, a few petrographic notes are included, and we have tried to accommodate mineralogical factors through the use of the CIPW norm. The norm generally gives a fair approximation of the mineralogical and modal composition of the common volcanic rocks as crystallized at low pressures under relatively anhydrous conditions.

The approach has been to try to find or devise simple graphical plots whereby the different rocks can be distinguished and named according to compositional fields that are reasonably consistent with current usage. The method has limitations because of the difficulties of representing chemically complex systems on graphs, and because many of the better-known, long-standing rock names have not been used in a consistent way over the years (Chayes 1970). However, the diagrams should not lead the user far astray, and if used with a certain amount of discretion, will generally give satisfactory classifications. Distinctions between the major series are based on suites of rocks more than on individual analyses so that, to the extent that the control data are representative and the diagrams discriminating, the dividing lines are fairly "natural boundaries". Subdivisions of series are necessarily more arbitrary, since continuums of compositions are generally involved, and the proposed boundaries tend to be a compromise between usage in the literature and geometric convenience.

²The spilite problem was recently reviewed by Amstutz (1968), who concluded that spilites are chemically different from basalts only through the phase separation (mineralogical differentiation) that accompanies the development of their characteristic mineral assemblages, which, he stated, commonly include abundant monomineralic portions of albite, chlorite, epidote, calcite, and amphibole. In the present context, the highly differentiated rocks at least would have to be considered "severely altered" and could not be classified on a magmatic basis. The spilite problem has also been discussed extensively by Vallance (1960, 1965).

The control data are from the references cited in Appendix I. They embody about 2500 analyses of rocks from several dozen different localities or environments, but are limited in time in that they come from rocks of either Precambrian or Cenozoic age.

Many plots of data points are presented to illustrate the basis on which boundaries and divisions are selected and to give an indication of how well the choices agree with current usage. The plots were originally prepared by computer by means of a line printer and are accurate to one-tenth of a graduated division horizontally and one-fifth of a division vertically, the spacings of the printer. The sources of the data shown on each diagram are listed in Appendix I. Appendix II gives a typical analysis of each of the rocks mentioned in Fig. 1; and will serve as a comparative guide either for a quick preliminary classification or for checking final results. Appendix III gives the equations of the proposed dividing lines; these can be used to make the classification by computer.

Preparation of Chemical Data Prior to Classification

Adjustments for Alteration

As it is intended that the proposed classification shall apply to metamorphosed as well as unaltered volcanic rocks, some comment on the possibility of chemical changes due to metamorphism or hydrothermal alteration, and on ways of adjusting for these, is in order. This is a complex problem much beyond the scope of this study. However, opinion expressed in the literature (e.g. Miyashiro 1968), and our own experience, indicates that the only constituents for which realistic adjustments can be made, at least in general studies, are the volatiles H_2O , CO_2 , and O_2 . The other constituents most likely to have been changed are the alkalis. Assuming that data for severely altered rocks have been avoided or rejected,³ the following two adjustments of the analytical data are recommended for consideration:

³The discrimination here may be based on any of field, petrographic, or chemical criteria; however, the possibilities appear so varied that we feel that the judgment as to where a cut-off should be made must rest with the user.

(1) Adjust the ratio $\text{Fe}_2\text{O}_3/\text{FeO}$ if it appears to have been changed. This ratio can appreciably affect the norm (e.g. Coombs 1963) and so may be critical in classification of the rock. The aim in making this adjustment should be to come as close as possible to the primary composition of the rock. In most cases the adjustment will necessarily be somewhat arbitrary, but it may be guided by (i) petrographic features such as the development of secondary magnetite, or the extent of ilmenite "exsolution" in magnetite, (ii) comparisons with data from less altered rocks in the same suite; and (iii) comparisons with data from fresh rocks of similar gross composition from other parts of the world. In general, oxidation is more common than reduction, so a smaller or limiting value for Fe_2O_3 is usually required. Coombs (1963, p. 233), for example, chose 1.5% Fe_2O_3 as an upper limit for basalts, and Chayes (1966) rejected analyses with $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios greater than 0.6. In the present work an upper limit on Fe_2O_3 is set according to the following equation (based on the observation that Fe_2O_3 and TiO_2 generally have similar trends of variation in unaltered volcanic series):

$$\% \text{Fe}_2\text{O}_3 = \% \text{TiO}_2 + 1.5$$

If the analysis value is less than this, no change is made; if it is greater, the "excess" is converted to FeO. The adjustment yields a more undersaturated norm.

(2) Recalculate the analysis to 100% without H_2O or CO_2 . This adjustment simply places all comparisons on the same basis. H_2O and CO_2 as measured in a rock analysis are not generally of interest in respect to magmatic composition (especially if the rock is metamorphosed), but if they amount to more than 2 or 3% they may significantly affect the values for other constituents simply through "dilution". However, this does not mean that the H_2O and CO_2 data should be forgotten—they are still significant chemical indicators of the state of alteration of the rock.

The above adjustments assume, in effect, that the rock was "open" only to volatiles during metamorphism or alteration, rather than to a more complex addition or removal of, say, magnetite, zeolites, or carbonate material. In general this assumption appears to be justified

by the results, but it should always be made with caution. Other adjustments probably should not be attempted without specific information on the nature and extent of the changes that might have occurred. As a rule, it is easier to detect a change than to correct for one, and if the problem appears untenable then the data should be rejected without attempting classification. We will not venture specific suggestions as to how alterations might be detected, except to note that they may be indicated by departures from normal patterns of variation in diagrams such as those presented below.

Adjustments for Phenocrysts and Xenocrysts

In dealing with highly porphyritic rocks it may be desirable to estimate the percentage and composition of phenocrysts or xenocrysts and calculate them out of the analyses before attempting classification. However, it appears that this is not commonly a problem of major concern (e.g. see Fig. 6).

Norm Calculations

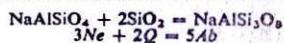
Norms are now generally calculated by computer, so their use is quite routine, and the CIPW conventions have been so widely used as to be preferable for general purposes. However, there is room for choice as to whether the results should be expressed in wt % as in the classical CIPW procedure, or in "percent cation equivalents" as in the so-called "molecular norm" or "Barth-Niggli katanorm" (Chayes and Metais 1964) (here referred to as the "cation norm"). Results derived from the two systems are generally similar, except that the ore-mineral values are only about two-thirds as large in the cation norm. Our computer program calculates both types, but we prefer the cation norm because it is better suited to graphical projection and easier to recast if one wishes to use alternative combining rules for specialized purposes. Also, the ore mineral values, in being smaller, are more like volume percentages and so relate somewhat better to modal data.

The norm notation used here is listed in Table 1. Note that in expressing normative feldspar compositions, *Ne* is recast as *Ab*. In this way the ratio of total *Ab* to *Or* is a true measure of the atomic ratio of sodium to potassium.

TABLE 1. Norm symbols used in the text

<i>Q</i>	— quartz, SiO ₂
<i>Or</i>	— orthoclase, KAlSi ₃ O ₈
<i>Ab</i>	— albite, NaAlSi ₃ O ₈
<i>An</i>	— anorthite, CaAl ₂ Si ₂ O ₈
<i>Ne</i>	— nepheline, NaAlSi ₃ O ₄
<i>Lc</i>	— leucite, KAlSi ₂ O ₆
<i>Ol</i>	— olivine, = <i>Fo</i> + <i>Fa</i> ≡ Mg ₂ SiO ₄ + Fe ₂ SiO ₄
<i>Opx</i>	— hypersthene, = <i>En</i> + <i>Fs</i> ≡ MgSiO ₃ + FeSiO ₃
<i>Cpx</i>	— clinopyroxene (augite) = <i>Di</i> + <i>He</i> ≡ CaMgSi ₂ O ₆ + CaFeSi ₂ O ₆
<i>Ac</i>	— acmite, NaFe ³⁺ Si ₂ O ₆
<i>Mt</i>	— magnetite, Fe ₃ O ₄
<i>Il</i>	— ilmenite, FeTiO ₃
<i>Hm</i>	— hematite, Fe ₂ O ₃
<i>Ab'</i>	— <i>Ab</i> + 5/3 <i>Ne</i> (see note)
Normative plagioclase composition = 100 <i>An</i> /(<i>An</i> + <i>Ab</i> + 5/3 <i>Ne</i>)	
= 100 <i>An</i> /(<i>An</i> + <i>Ab'</i>)	
Normative color index = <i>Ol</i> + <i>Opx</i> + <i>Cpx</i> + <i>Mt</i> + <i>Il</i> + <i>Hm</i> + <i>Ap</i>	

NOTE: This equation converts *Ne* to *Ab* based on the relations:



Thus each unit of *Ne* gives 5/3 units of *Ab*.

Primary Division of the Major Series

Historical Review and Some Basic Features of the Present Classification Scheme

The term "calc-alkali" was originally applied to igneous rocks in which the proportions of lime and alkalis (in relation to other constituents) are such that the dominant minerals are feldspars, hornblende, and (or) augite, with alkali-rich minerals such as feldspathoids and sodic pyroxenes and amphiboles being specifically absent (Holmes 1920). It served to contrast these rocks—principally gabbros, diorites, and granodiorites, and their volcanic equivalents—from "alkaline rocks". Peacock (1931) proposed a more specific chemical definition whereby calc-alkali series are those in which (Na₂O + K₂O) exceeds CaO at SiO₂ values between 55 and 61%. However, the more recent tendency, originating with Wager and Deer's (1939) work on the Skaergaard intrusion, has been to identify the series by its trend of variation in the AFM diagram of igneous petrology (see Fig. 2, E and F).

The basic framework of present day classifications was set by Kennedy (1933) and Tilley (1950). Kennedy presented evidence for two primary basalt magmas: an "olivine basalt magma type" parental to an alkaline line of magmatic descent ending with trachyte and phonolite; and a "tholeiitic magma type" leading to a more siliceous association, ending with rhyolite, that he equated with the calc-alkali series. Tilley removed an ambiguity in nomen-

clature by substituting "alkali olivine basalt" for "olivine basalt", and he pointed out that the tholeiitic basalt series is distinctive from the calc-alkali series in that the associated andesite is generally only a minor rock relatively rich in iron, whereas in calc-alkali suites of (Cenozoic) orogenic belts, andesite is the dominant rock and usually has more Al₂O₃ and lower Fe/Mg ratios than its tholeiitic counterpart. However, like Kennedy, Tilley considered the calc-alkali series to be a tholeiitic derivative.

Kuno (1960) postulated that there was a third primary magma, which he called "high-alumina basalt", and he chose to define a high-alumina basalt series comprising andesite, dacite, and rhyolite, distinct from either the tholeiitic basalt or calc-alkali series (see also Kuno 1968). Yoder and Tilley (1962, p. 335) disagreed, being of the opinion that high-alumina basalts occurred as variants of both tholeiitic and alkali olivine basalts. Wilkinson (1968a) took still another view and treated high-alumina basalt as the principal basalt of the calc-alkali series.⁴ During the same period, Chayes (1965) reviewed the history of the term "tholeiite" and argued that it should be abandoned, recommending as an alternative "subalkaline basalt". However, Tilley and Muir (1967) defended its use, and judging from its

⁴Wilkinson's view is consistent with earlier work by Nockolds and Allen (1953), who compiled ten analyses of "parental magmas" of calc-alkali series, all of which are high-alumina basalts.



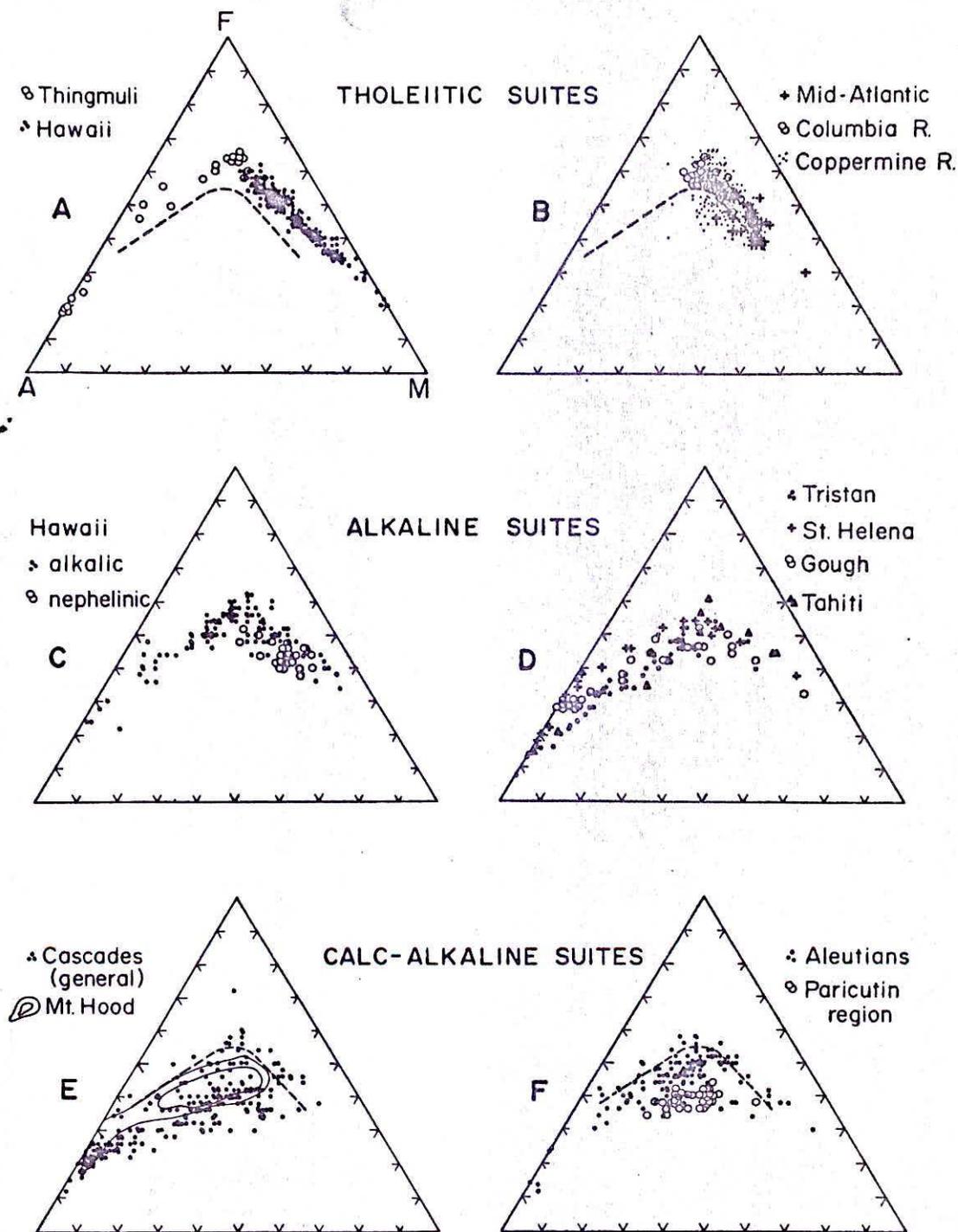


FIG. 2. AFM plots comparing the patterns of variation of suites of generally tholeiitic, alkaline, and calc-alkaline rocks. A = $\text{Na}_2\text{O} + \text{K}_2\text{O}$; F = $\text{FeO} + 0.8998 \text{Fe}_2\text{O}_3$; M = MgO , all in weight percent. The dashed line in Plots A, B, E, and F serves to separate tholeiitic and calc-alkaline compositions after alkaline compositions have been eliminated (see Figs. 3, 4, and 5).

continued frequent appearance in the literature, the term has won general acceptance. Wilkinson (1968a) subsequently used "subalkaline" as a more general name for rocks of both the tholeiitic basalt and calc-alkali series (as opposed to alkaline rocks).

In the classification presented here (Fig. 1), which is very like Wilkinson's (1968a), the following features should be noted:

(1) The three main series—the tholeiitic basalt, calc-alkali, and alkali olivine basalt series—are those established by Kennedy (1933) and Tilley (1950). However, no implications are intended as to genesis: the series are used simply because they appear to be natural divisions.

(2) "Subalkaline" is used in the manner of Wilkinson (1968a) to include both the calc-alkali and the tholeiitic basalt series. Employed in this way it is a convenient term to distinguish these rocks from the alkaline and peralkaline rocks, and at the same time its meaning is consistent with that intended by Chayes (1966).

(3) The calc-alkali series is defined on the basis of the AFM diagram, using as typical examples Cenozoic basalt-andesite-dacite-rhyolite suites from the North American Cordillera (Fig. 2, E, F). On this basis *most* high-alumina basalts fall in the calc-alkali series. There are a few, such as the Skaergaard magma (Wager and Deer 1939) and the Warner basalt in California (Kuno 1968, Fig. 26) that have differentiated along trends of iron-enrichment such as characterize tholeiitic magmas; and these may constitute a different type of high-alumina basalt (Smith and Carmichael 1968, p. 232). However, the differences are not sufficiently great to make the distinction practical in a general classification scheme such as this. Also, we have not been able to distinguish consistently between the more siliceous members of the calc-alkali and tholeiitic basalt series—between the rhyolites especially but, to some extent, the dacites as well. The approach, therefore, is to treat the

tholeiitic basalt and calc-alkali series as being transitional along various alternative "avenues" designed to represent the rock associations observed in volcanic suites. Thus in Fig. 1: (i) the tholeiitic basalt series may end with rhyolite (as in Thingmuli volcano, Iceland; Carmichael 1964); (ii) tholeiitic basalts may be associated with calc-alkaline andesites, dacites, and rhyolites (as in the Yellowstone volcanic suite; Baragar 1966); (iii) tholeiites may be closely associated with high-alumina basalts (as in the Noranda volcanic belt; Baragar 1968); and (iv) high-alumina basalt may "evolve into" an iron-enriched magma (as it did in the Skaergaard intrusion).

(4) The alkali olivine basalt series is split on the basis of K_2O/Na_2O ratios, following Tilley and Muir (1964), and others.

Finally, we re-emphasize that, although the associations outlined in Fig. 1 may also represent paths of magmatic differentiation, the classification itself is intended to be essentially non-genetic. For example, the fact that high-alumina basalt is shown at the top of the calc-alkali series carries no implication that it is a primary magma, that it is necessarily the parent magma of the calc-alkali series, or even that it must always be present in calc-alkali associations. In the context of this report, a series is distinguished by certain characteristics, not by genesis, and it does not have to be represented by all of its members in order to be identified.

Some General Characteristics of the Major Divisions

At the present stage of earth history, the calc-alkali series is most prominent in the Circum-Pacific region where it is typified by the basalt-andesite-dacite-rhyolite associations common to the many large "andesitic volcanoes". However, it is also abundant in the eugeosynclinal successions of Archean "greenstone" belts, where it is associated with tholeiitic basalt, and it probably has similar occurrence in volcanic belts of other ages. The tholeiitic basalt series is the dominant series of the large plateau basaltic provinces of the

world (e.g. the Columbia River basalts and the Drakensburg basalt – Karroo dolerite province); it forms some of the major oceanic islands (Hawaii, Iceland); and it apparently underlies much of the ocean floor. It is also the main component of Archean greenstone belts. The alkali olivine basalt series most commonly occurs in small cone volcanoes and is especially prominent in this form on the oceanic islands (where it evidently caps a tholeiitic foundation; MacDonald and Katsura 1964; Engel *et al.* 1965) and along the interior parts of certain island arcs (Kuno 1959, 1966). On the continents it occurs in minor plateau-type flows (e.g. in the Hebrides), as small volcanoes within orogenic belts, and in association with major block faulting (as in the East African rift valleys).

Rocks of the tholeiitic basalt and calc-alkali series typically show *Opx* in the norm and may have *Q*, whereas most rocks in the alkali olivine basalt series and all the nephelinitic and analcitic rocks have *Ne*. Most leucitites also show *Ne*, but there are some leucite-rich volcanic rocks that show *Opx* and even *Q* (e.g. wyomingites; Carmichael 1967). In the AFM diagram, tholeiitic and alkaline suites commonly show a strong trend of iron-enrichment at low levels of ($K_2O + Na_2O$), and then swing to rapid alkali enrichment (Fig. 2A–2D). Calc-alkaline suites trend more directly across the diagram with more gradual enrichment in iron (Fig. 2E, F).

The distinction of the subalkaline and alkaline series is most difficult in the basaltic range, and here the pyroxenes are particularly important. The typical pyroxenes of tholeiitic and calc-alkaline volcanics are Ca-poor types—subcalcic augite, hypersthene, and pigeonite—and in Japan the tholeiitic series has been identified as the “pigeonitic series” and the calc-alkali series as the “hypersthene series”, based on a mineralogical contrast that seems mainly to reflect Fe/Mg ratio (Kuno 1968). Rocks of the alkali olivine basalt series generally contain Ca-rich augite, commonly a titaniferous variety characterized by lavender colors. Hypersthene and pigeonite are rare.

Tholeiitic rocks are not generally conspicuously porphyritic; the most common phenocrysts are olivine and pyroxene. In calc-alkaline rocks, plagioclase is the dominant phenocryst, with olivine, hypersthene, and hornblende oc-

curing in subordinate amounts. Alignment of the plagioclase laths may impart a platy appearance. In both series, olivine may show evidence of resorption or reaction to a Ca-poor pyroxene; the groundmass commonly contains interstitial quartz (or other silica minerals, or silica-rich glass); and pegmatitic facies typically contain quartz and may be granophyric.

In the alkali olivine basalt series, the phenocrystic minerals are plagioclase, augite, and olivine, any of which may predominate, and the intermediate to acidic rocks commonly show a strongly trachytic texture due to planar alignment of plagioclase laths. The olivine shows little or no evidence of resorption and may be abundant in the groundmass together with alkali feldspar. Feldspathoids and analcite are common in the groundmass and in pegmatitic schlieren, whereas silica minerals are rare.

The peralkaline rocks, as defined by Shand (1951), have molecular $(Na_2O + K_2O) > Al_2O_3$, which means that they will show *Ac* in the norm. Mineralogically, they commonly contain sodic pyroxenes (aegerine and aegerine augite) and sodic amphiboles (richterite, barkevikite), and they may contain other relatively diagnostic minerals such as melanite and eudialyte. Probably the most common peralkaline rocks are high-silica types of grossly rhyolitic composition called pantellerite and commendite. A system of classification for these and associated rocks is given by Noble (1968).

For more detailed information on the physical, mineralogical, and petrographic features of the rocks mentioned above the reader is referred to papers by Wilkinson (1968a) and Brown (1968), to the references listed in Appendix I, and to standard text books.

Alkaline versus Subalkaline Compositions

Various diagrams have been used in the literature to distinguish alkaline and subalkaline volcanics; three are considered here: (1) a wt % plot of $(Na_2O + K_2O)$ against SiO_2 ; (2) a tetrahedral diagram with apices at the compositional points of *Ol*, *Cpx*, *Ne*, and *Q*; and (3) a ternary plot, *Ol*–*Cpx*–*Opx* (Chayes 1966).

(1) The Alkalies-Silica Diagram

This diagram is convenient since it makes direct use of the analytical data. It has been established as an effective means of distinguish-

ing alkalic and tholeiitic rock from Hawaii, as illustrated by the Hawaiian data and MacDonald's (1968) dividing line in Fig. 3A (see also Tilley 1950; MacDonald and Katsura 1964), and it has been widely used by other authors (e.g. Kuno 1968).

The diagram has been tested further in this study using data from other volcanic suites, some of which are illustrated in Fig. 3B-3E. Results indicate that the curved line shown in these plots should give somewhat better separation of alkaline and subalkaline compositions for general studies than the Hawaiian line. By means of this curve about 90% of the analyses in our control data are classified satisfactorily, and most suites are placed correctly on a statistical basis. However, there are important exceptions. The Coppermine River lavas, for example, generally have *Opx* in the norm, and commonly *Q*, and certainly are broadly tholeiitic in their overall characteristics; yet more than half of the available analyses fall in the alkaline field (Fig. 3F). It appears therefore that the diagram has definite limitations and should be used with care. The norm plots appear somewhat more dependable, presumably because they reflect the interrelation of more constituents.

(2) The *Cpx-Ol-Ne-Q* Tetrahedron

This diagram was introduced by Yoder and Tilley (1962) as a means of classifying basaltic rocks because of its similarity to simplified basalt systems studied in the laboratory. They pointed out that the intermediate plane *Cpx-Ol-Ab*, which they termed "the critical plane of silica undersaturation", is very nearly coincident with a low-pressure liquidus thermal divide that effectively separates the differentiation trends of tholeiitic and alkaline magmas. Since this plane separates compositions with *Ne* in the norm from those with *Opx*, they considered this distinction a practical criterion for classification. However, Poldervaart (1962, 1964) contended that the thermal divide was significantly on the *Opx*-normative side; and this appears to be substantiated in that several major alkali olivine basalt suites trend along the *Ol-Cpx-Ab* plane partly in the *Opx*-normative region, whereas rocks of tholeiitic basalt and calc-alkali suites only rarely show *Ne*. Poldervaart (1964) suggested that a better separation would be given by a plane hinged from the *Cpx-Ol* edge of the tetrahedron, ex-

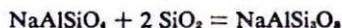
tending to the point $Ne_{47}Q_{53}$ on the opposite edge.⁵

As with the alkalis-silica diagram, an attempt has been made to establish a natural division based on data from *suites* of volcanic rocks. For plotting purposes, Poldervaart's lead is followed and the contents of the tetrahedron are projected from *Cpx* onto the basal triangle $Ol'-Ne'-Q'$.⁶ This view is especially useful because it separates rocks with *Ne*, (*Opx* + *Ol*), and (*Opx* + *Q*) in the norm (i.e. the "critically undersaturated", "undersaturated" and "oversaturated" rocks), and because the dividing planes proposed by Yoder and Tilley (1962) and by Poldervaart (1964) are both reduced to lines (Fig. 4). Several of the plots investigated and the line chosen as an effective divider are shown in Fig. 4. The line follows the $Ol'-Ab$ join along part of its length and then bends into the *Opx*-normative region and extends to *Q*-normative compositions in order to accommodate certain trachytic rocks. The discrimination it gives is generally good. A few of the Coppermine River lavas still fall in the alkaline field (presumably because they are truly alkalic), but the worst offenders are the Hawaiian alkaline rocks and this is due at least partly to the following rather special circumstances:

(1) The Hawaiian alkaline rocks are uncommonly high in both Fe_2O_3 and TiO_2 ; hence our adjustment limit for

⁵Poldervaart (1964, p. 233) originally defined the surface in wt %, and the coordinate given here has been recalculated for the cation norm.

⁶Using the cation norm the position of *Ab* on the *Ne-Q* join is determined by the equation



which in cation equivalents is written

$$3Ne + 2Q = 5 Ab$$

Thus *Ab* plots at Ne_3Q_2 , or $Ne_{60}Q_{40}$. Similarly, hypersthene is located by the equation



or, $3Ol + 1Q = 4 Opx$, and so plots at Ol_3Q_1 , or $Ol_{75}Q_{25}$.

To plot the basal projection of the tetrahedron, *Ab* and *Opx* are recalculated according to the same equations, and the coordinates of the ternary diagram (before normalization to 100%) become:

$$\begin{aligned} Ne' &= Ne + \frac{1}{3} Ab \\ Q' &= Q + \frac{1}{3} Ab + \frac{1}{3} Opx \\ Ol' &= Ol + \frac{1}{3} Opx \end{aligned}$$

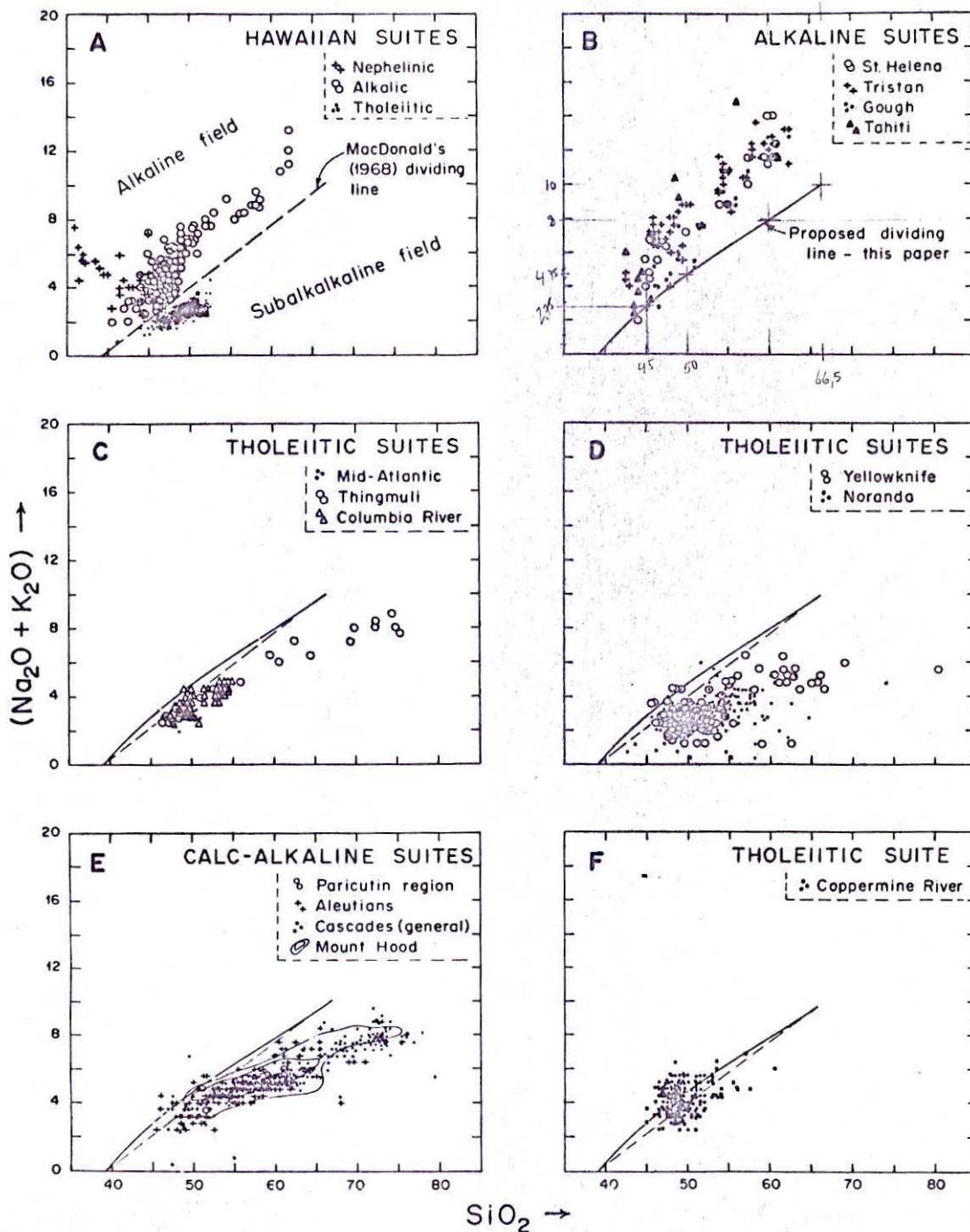


FIG. 3. Alkalies-silica plots comparing suites of predominantly tholeiitic, alkaline and calc-alkaline volcanic rocks. The dashed line is MacDonald's (1968) dividing line for Hawaiian tholeiitic and alkaline rocks (Plot A); the solid curve is the line chosen in the present investigation for making a general distinction between alkaline and subalkaline compositions (Plot B). The classification of each Hawaiian rock in A is that of the original author. Plots in wt %.

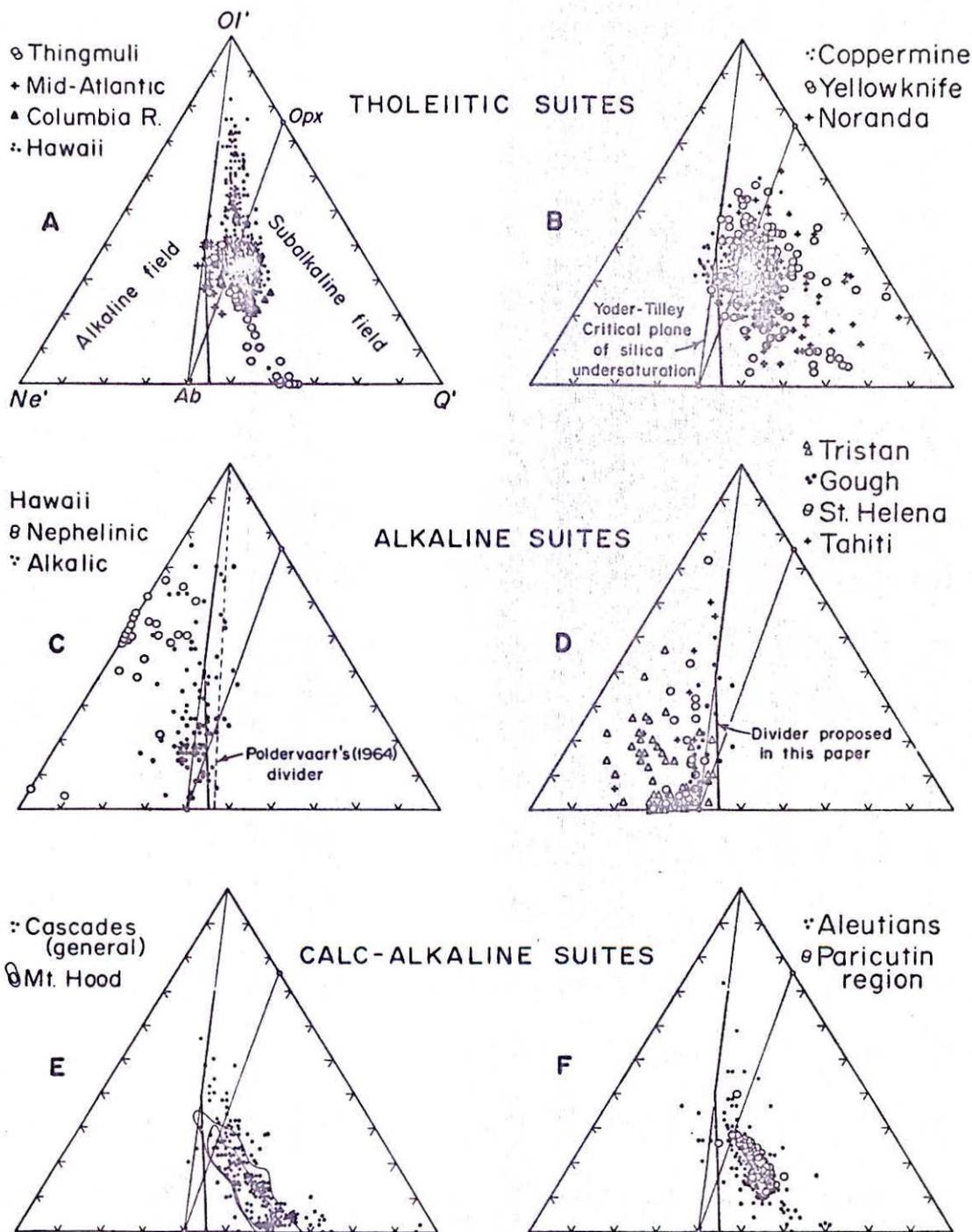


FIG. 4. OI' - Ne' - Q' projections of suites of predominantly tholeiitic, alkaline and calc-alkaline volcanic rocks. Note the traces of Yoder and Tilley's (1962) "critical plane of silica saturation" (Plot B) and Poldervaart's (1964) dividing plane for separating tholeiitic and alkaline rocks (Plot C). The heavy solid line is the dividing line for alkaline and subalkaline rocks proposed in this paper (Plot D). Plots in % cation equivalents based on the cation norm.

Fe_2O_3 may not be sufficiently stringent for them.

(2) There is a closer physical and stratigraphic association of alkaline and tholeiitic rocks at Hawaii than in most volcanic centers, with the apparent effect that there are more "transitional rocks", most of which have been classed as alkaline. Also, the Hawaiian tholeiites are rather exceptionally high in *Opx*, and consequently the transitional rocks tend also to be high in this component.

(3) The *Cpx-Ol-Opx Ternary*

This diagram is also a projection of the *Cpx-Ol-Ne-Q* tetrahedron, but of only a part. In suggesting its use, Chayes (1965, 1966) noted that basic volcanics with *Ne* in the norm are almost invariably alkaline, and those with *Q*, subalkaline; the problematical ones are the *Opx*-normative types with $(\text{Ne} + \text{Q}) = 0$, and these plot exclusively in the *Cpx-Ol-Opx* ternary. Chayes chose to make the alkaline-subalkaline distinction on a purely empirical basis. He divided his sample of Cenozoic basic volcanics with $(\text{Ne} + \text{Q}) = 0$ into two groups, depending on whether they were more intimately associated with *Ne*-normative or with *Q*-normative rocks. After rejecting analyses of rocks he considered to be excessively altered, he determined lines that gave the best statistical separation using discriminant functions. The two lines he derived are shown in Fig. 5. The straight one is for the linear discriminant function; the curve, for the linear plus quadratic function. Their equations, respectively, are:

$$X_{\text{Opx}} + 0.134X_{\text{Ol}} = 26.942$$

and

$$(X_{\text{Opx}} + 1.119X_{\text{Ol}}) - (0.006X_{\text{Opx}}^2 + 0.014X_{\text{Opx}}X_{\text{Ol}} - 0.011X_{\text{Ol}}^2) = 32.264$$

where X_{Opx} and X_{Ol} are the proportions of *Opx* and *Ol* in a wt % ternary plot. If, for a particular analysis, the left-hand side of the equation under consideration is less than the right, the rock is alkaline; if greater, it is subalkaline.

Chayes estimated that the efficiency of the curved line (which gave the best discrimination) was only about 78% within the ternary diagram, but he noted that only a small proportion of all basic volcanics have $(\text{Ne} +$

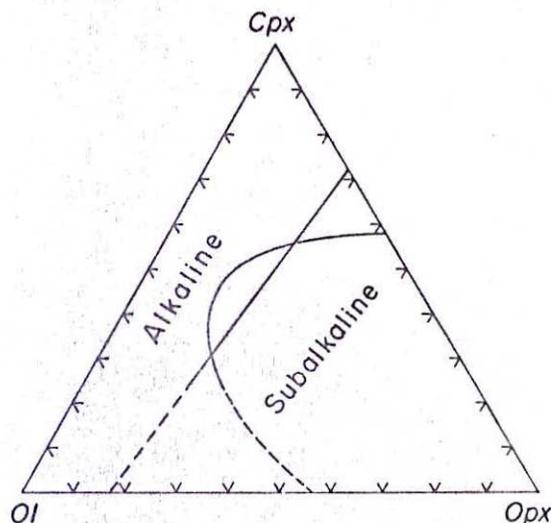


FIG. 5. *Cpx-Ol-Opx* ternary showing the discriminant functions determined by Chayes (1965, 1966) for separating alkaline and subalkaline basic volcanics. Plots in wt %. See text for explanation.

$\text{Q}) = 0$, so that when an overall sample was considered, the efficiency was about 96%.

We are a little doubtful that the *Cpx-Ol-Opx* projection is the best one in which to make an alkaline-subalkaline distinction, even though it excludes all but the most critical rocks, but Chayes' study of the problem is the most detailed (and most elegant) that has been attempted and on that basis may be the best to use in the final analysis. The main problem area appears to be with basalts from the ocean floor. Many of these that are now called tholeiites would be classed as alkaline using Chayes' discriminants. From a practical viewpoint, one should note that the dividing lines are derived for, and therefore should be applied only to, basic volcanics; they do not pertain to the more acidic (siliceous) rocks.

The Calc-alkali Series versus the Tholeiitic Basalt Series

The Calc-alkali series generally comprises a large proportion of andesite, dacite, and rhyolite. Chemically, it is most commonly identified by its trend or position in the AFM diagram, where it is separated from the tholeiitic rocks by a dividing line such as the one shown in Fig. 2.

However, the most prominent chemical difference between the more basic members of typical calc-alkali and tholeiitic series of Ceno-

zoic age is in their alumina content. The calc-alkaline basalts and andesites are generally high-alumina types containing 16 to 20% Al_2O_3 , whereas their tholeiitic counterparts have only 12 to 16%. This difference is especially well illustrated by the plots of Al_2O_3 versus normative plagioclase composition in Fig. 6, where a convenient dividing line is drawn from very calcic plagioclase compositions down to about An_{35} (i.e. to somewhere in the andesite range; see Fig. 7). Within this range this type of diagram appears to provide a more significant separation of the two series than the AFM plot. It is on the basis of Fig. 6 that high-alumina basalt and high-alumina andesite are assigned to the calc-alkali series (Fig. 1).⁷

For the more acidic compositions, extending into the dacite range, iron-enrichment is the dominant feature of contrast and the AFM diagram gives the better separation. However, neither plot successfully separates the rhyolites associated with the two series, and therefore all rhyolites are placed in the calc-alkali series (Fig. 1).

Nephelinitic, Leucitic, and Analcitic Rocks versus the Alkali Olivine Basalt Series

One supposes that leucitites and analcites can generally be identified petrographically. Nephelinites may present more problems, but judging from the little data we have been able to compile, they fall in reasonably distinctive areas in the alkalis-silica diagram (Fig. 3A), the $Ol'-Ne'-Q'$ projection (Fig. 4C) and in a plot of normative color index versus normative plagioclase composition (Fig. 10). In general, they are characterized by SiO_2 content less than 45% and normative color indices greater than 50; they have large Ne/Ab ratios, and in some cases they have Lc in the norm. Combinations of these features should readily distinguish them from the typical rocks of the alkali olivine basalt series.

As mentioned previously, the detailed classi-

⁷It is perhaps worth emphasizing that an Al_2O_3 -content of 16% or greater is not in itself sufficient to categorize a basic volcanic rock as a high-alumina basalt or andesite. As it is defined here, which in essence is the way it was originally defined by Kuno (1960), a high-alumina basalt is a *subalkaline* rock. There are many trachybasalts, tristanites, hawaiites, and mugearites that also contain more than 16% Al_2O_3 (Appendix II), but they are alkaline.

fication of the nephelinites, leucitites, and analcites is not attempted. The reader is referred to standard textbooks and to a few recent papers (e.g. MacDonald and Katsura 1964; MacDonald 1968; Carmichael 1967; and Wilkinson 1968b).

Subdivision of the Main Series

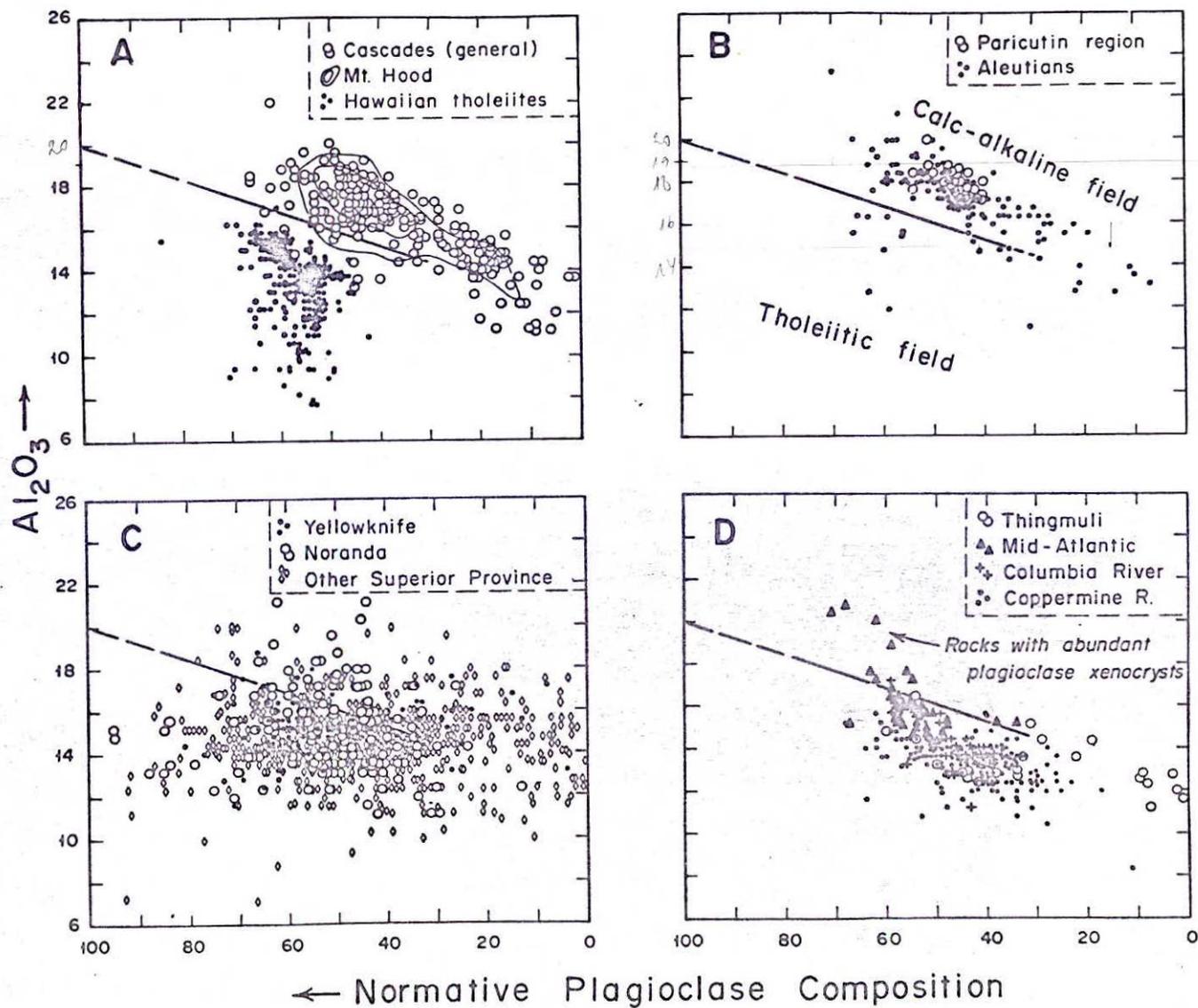
Tholeiitic Basalt Series

Petrographically, this series is commonly divided into the following rock types: tholeiitic picrite-basalt; olivine tholeiite; tholeiite; quartz tholeiite; and tholeiitic andesite. However, the three kinds of tholeiite cannot be distinguished chemically because (a) many olivine tholeiites are Q -normative; and (b) the presence of small amounts of Ol in the norm is no guarantee that olivine is (or was) present modally. Without some petrographic control one can probably only distinguish "undersaturated" and "oversaturated" tholeiites, based on the presence of Ol or Q in the norm.

A picrite-basalt by definition carries a large proportion of phenocrystic olivine, a feature that should generally show in the amount of Ol in the norm. Inspection of the literature suggests that 25% Ol is a practical minimum, and MacDonald and Katsura (1964, p. 88) specified that feldspar content (in this case, the sum of Ab , An , and Or) should be less than 30%. The name oceanite was used in place of tholeiitic picrite-basalt by MacDonald and Katsura (1964, p. 88), but Wilkinson (1968a, p. 201) considered oceanites to be alkaline rocks.

Andesite is defined in this paper on the basis of Fig. 7 (which is discussed in detail in the next section) with the one additional stipulation that it should generally contain at least 5–10% Q (Chayes 1965, 1969). We have in effect taken Thingmuli volcano, Iceland as the type locality of tholeiitic andesite; and the term is used to cover both the "basaltic andesites" and the "icelandites" of Carmichael (1964, pp. 440–442). The rock is distinguished from calc-alkaline andesites in that it shows more iron-enrichment in the AFM diagram (Fig. 2), and it tends to have more sodic plagioclase at the equivalent color index (Fig. 7).

Icelandite is a very iron-rich variant of andesite or dacite. At Thingmuli it contains 59–65% SiO_2 and 15–25% Q ; the ratio



Fe/(Fe + Mg) ranges from 0.72 to 0.87; norm plagioclase, from An_{15} – An_{30} ; and normative color index, from 15 to 25.

It is commonly considered important to distinguish K-rich and K-poor tholeiitic rocks, and some approximate guide lines are suggested in the An – Ab' – Or projections in Fig. 8.

Calc-alkali Series

In the literature, subdivisions of the calc-alkali series are variously based on color index, plagioclase composition, silica content, quartz content, and numerous other petrographic and chemical criteria. Consequently any system of classification that attempts to be consistent with previous usage must be a compromise. The definitions and differences of basalt and andesite have received considerable attention in the recent literature (e.g. Chayes 1969; Coats 1968; Wilkinson 1968a), and Chayes (1970) has given some attention to dacite.

After considerable investigation we have settled on a plot of normative color index versus normative plagioclase composition as a reasonably satisfactory, simple, diagram for classifying all subalkaline basalts, andesites, dacites, and rhyolites (Fig. 7). Further division into K-poor "average", and K-rich types can be made by means of an An – Ab' – Or projection (Fig. 8). The first diagram has the important feature that the two parameters on which it is based relate fairly closely to the corresponding petrographic quantities; it should therefore be useful for a petrographic-mineralogical classification as well as for chemical classification. Its principal shortcoming is that normative plagioclase composition is strongly dependent on Na_2O and so may be fairly sensitive to changes imposed by alteration or metamorphism. A plot of color index versus silica would probably be more reliable in this respect, but does not seem to give as good discrimination in terms of the way the various rock types have been named in the literature.

Data from the Cascades and Thingmuli vol-

cano constitute the main control for classification in Fig. 7, but the divisions are reasonably consistent with classifications employed in the Aleutian Islands and in the Paricutin region of Mexico. The proposed basalt–andesite boundary delimits fairly well the range of most tholeiitic basalts. Of particular note is that, because the dividing lines are sloped, both parameters are necessary to enable classification. Previous classifications in which color index and plagioclase composition have been used as a basis have tended to be built on either one or the other. For example, Johannsen (1937) made the basalt–andesite division at an average plagioclase composition of An_{50} , whereas Shand (1951) put it at a color index of 30. By our system a basalt should be normative plagioclase as sodic as An_{30} if its color index is as high as 40, or its color index may be less than 20 if its plagioclase is more calcic than An_{60} .

The term basaltic andesite has been widely used in the literature, but its definition is very obscure. A review by Coats (1968, pp. 692–693) suggests that it should apply to basic volcanics with phenocrysts of labradorite or bytownite and SiO_2 in the range 54–58%; but the analyses he compiled (Coats, 1968, Table 1 and Fig. 4) do not fall in a distinctive field in any plots we have investigated; they simply straddle potential basalt–andesite boundaries along the general trend of the calc-alkali series. It is suggested, therefore, that if the term is to be used, it should be restricted to andesites with relatively calcic normative plagioclase and low color index; it would then be the approximate antithesis of icelandite (Fig. 7).

The most arbitrary dividing line in Fig. 7 is between andesite and dacite—simply because this distinction is extremely vague in the literature (cf. Chayes 1970). Also, we have found no consistency in the use of the term rhyodacite: the name suggests a rock intermediate between dacite and rhyolite, and Williams *et al.* (1954, p. 121) classed the rock as being richer in alkali feldspar than dacite, but neither of

FIG. 6. Plots of wt % Al_2O_3 versus normative plagioclase composition contrasting suites of predominantly tholeiitic and calc-alkaline volcanic rocks and showing a proposed dividing line for the more basic members. Plot C shows that the Canadian Archean volcanics are mainly tholeiitic with some calc-alkaline variants. Note the effect of plagioclase xenocrysts in some of the lavas from the Mid-Atlantic ridge (data from Aumento 1968), and how this effect is not generally apparent in the other data.

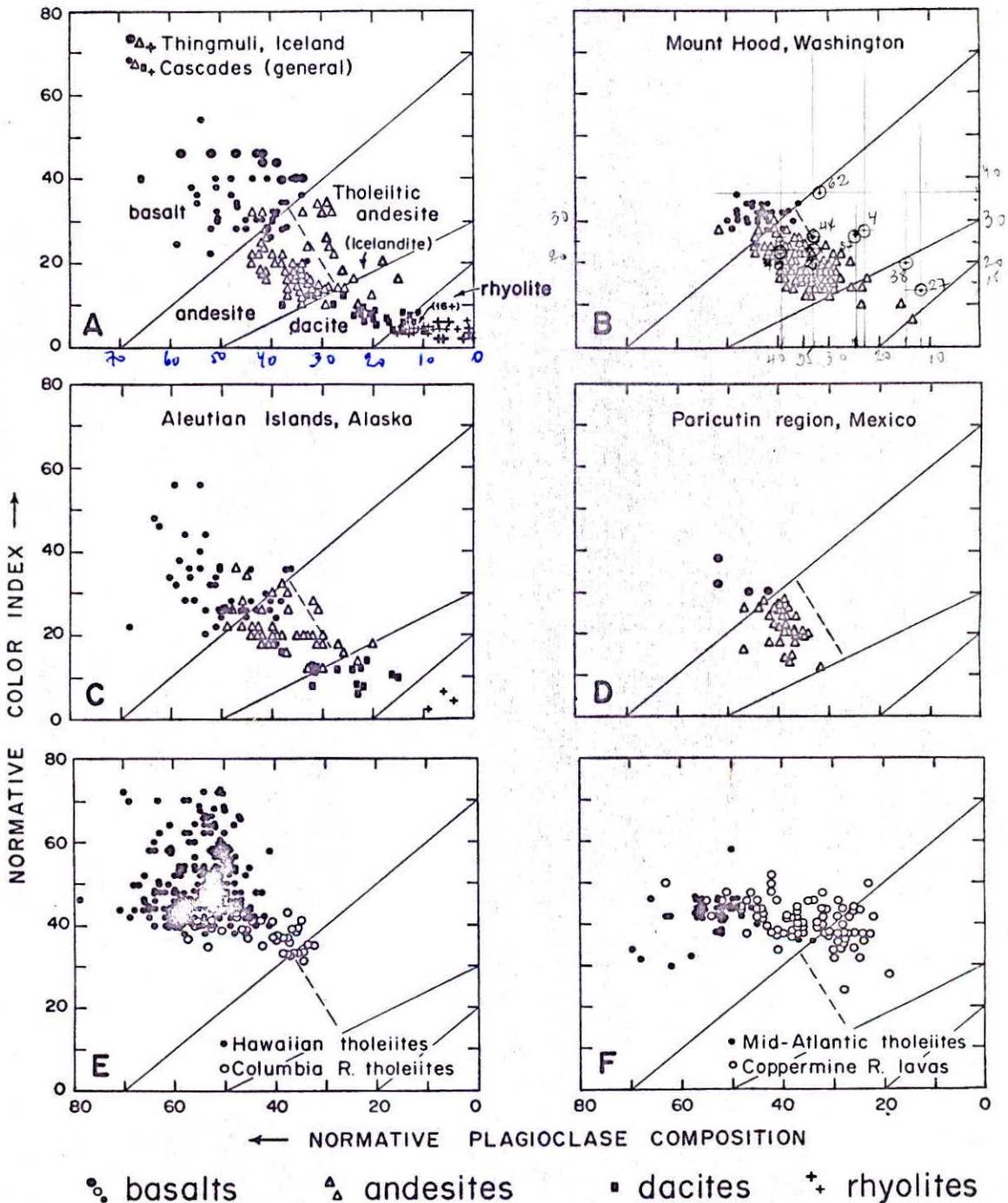


FIG. 7. Plots of normative color index versus normative plagioclase composition for suites of subalkaline rocks, showing proposed dividing lines for distinguishing basalts, andesites, dacites, and rhyolites. A provisional field is assigned to tholeiitic andesite. The symbols for the data points are based on the names assigned by the authors from whom the data were obtained (see Appendix I). In only a few cases, where an author was obviously badly out of step with the others, have the available data not been used. Plots in % cation equivalents.

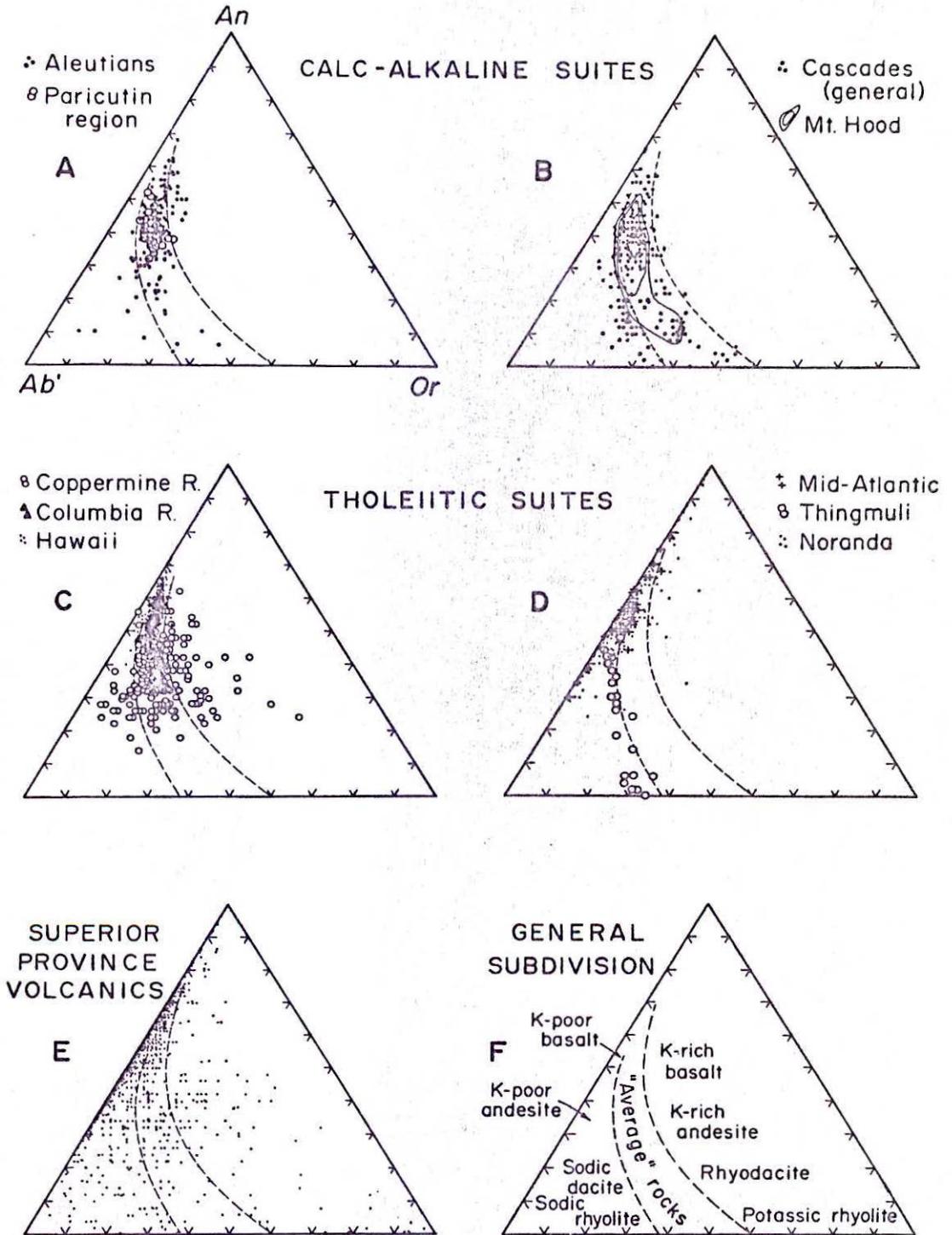


FIG. 8. *An-Ab'-Or* projections of suites of subalkaline rocks showing provisional boundaries for distinguishing K-poor, "common", and K-rich variants. The plot of Superior province volcanics serves to emphasize the need for such classification. Plots in % cation equivalents.

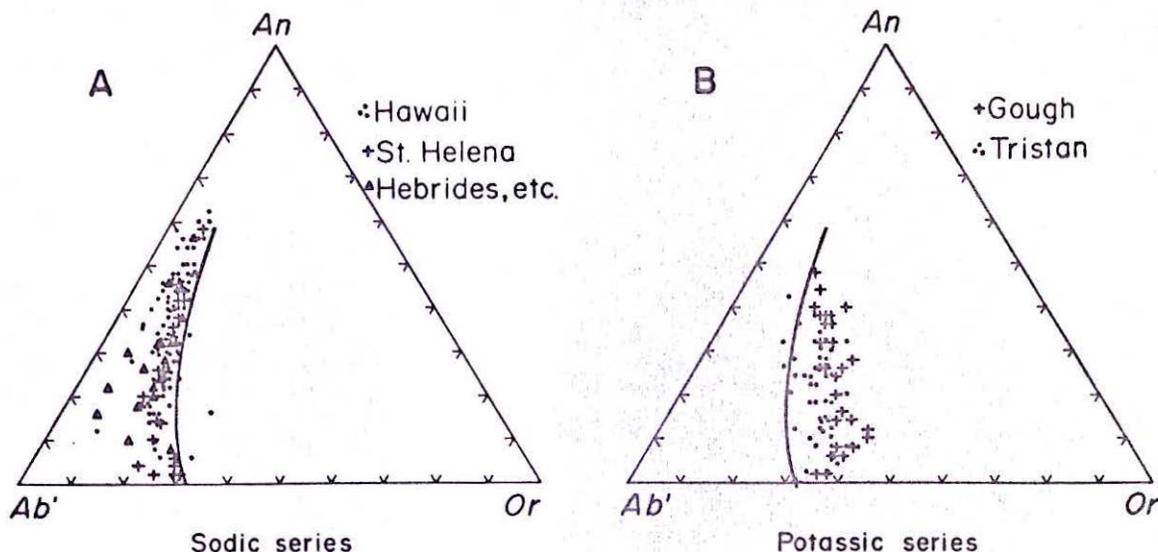


FIG. 9. $An-Ab'-Or$ projections contrasting the two main alkali olivine basalt series, showing a proposed dividing line. The data for the points labelled "Hebrides, etc." are from the compilation by Muir and Tilley (1961). Plots in % cation equivalents.

these features is evident in the limited chemical data at hand. On the other hand, the name could usefully be applied to K_2O -rich dacites as suggested in the $An-Ab'-Or$ plots in Fig. 8F. Rocks of this composition are common in Archean volcanic belts (Fig. 8E) and are very different from the usual calc-alkali dacite.

Rhyolite presents less problem than dacite, the term being generally applied to volcanics with 70–75% SiO_2 , and normative color index and plagioclase composition as in Fig. 7. Most obsidians and pitchstones are rhyolites. Distinction of potassic and sodic types in a manner such as suggested in Fig. 8 appears worthwhile.

Alkali Olivine Basalt Series

Two principal series of rocks are currently recognized in association with alkali olivine basalts: a "sodic series", hawaiite–mugearite–benmorite–trachyte, common to the Hawaiian Islands (MacDonald and Katsura 1964; MacDonald 1968) and Hebrides (Muir and Tilley 1961); and a "potassic series", trachybasalt – tristanite – trachyte, typical of Tristan da Cunha (Baker *et al.* 1964) and Gough Islands (LeMaitre 1962). Both series have mafic derivatives as well, called alkalic picrite–basalt and ankaramite, but it is doubtful that they can consistently be distinguished in this part of their range as the rocks involved are rather low in alkalis.

The term "trachyandesite" has commonly been applied to the intermediate rocks in the trachybasalt–trachyte association, but Tilley and Muir (1964) argued strongly against its use and recommended "tristanite" as an alternative. We concur on the grounds that the rocks in question are very different from the oversaturated andesites typical of the calc-alkali and tholeiitic basalt series. The different name helps to avoid confusion.⁸

Three diagrams are used to classify the rocks of the alkali olivine basalt series: an $An-Ab'-Or$ plot to separate the two series (Fig. 9), and individual plots of normative color index versus normative plagioclase composition to subdivide these (Figs. 10 and 11). The proposed dividing lines are generally consistent with nomenclature used in the reference literature, with the notable exception that the intermediate rocks of St. Helena Island plot in the hawaiite and mugearite fields, whereas Baker (1969) classified them as trachybasalts and trachyandesites (Fig. 9).

An alkali picrite–basalt, like its tholeiitic counterpart, should contain a large amount of modal olivine, and this should show in its norm.

⁸The prefix "trachy" also is undesirable in a chemical classification because of its textural connotation, but its use in trachybasalt has been accepted by most authors, apparently for want of better alternatives.

A minimum of 25% *Ol* appears again to be a practical limit. Ankarmites are very rich in phenocrystic augite and generally carry some olivine phenocrysts. Most of the available analyses of ankarmites show at least 20% *Cpx*.

It may be of interest to make further subdivision of the alkali olivine basalt series on the presence or absence of feldspathoids (Coombs and Wilkinson 1969). In some cases at least this distinction shows in the percentage of *Ne* in the norm: thus among the rocks assigned to the trachybasalt-tristanite-trachyte series, those from Tristan da Cunha are more commonly feldspathoidal and have more *Ne* than the Gough Islands suite (Fig. 9). Note that the feldspathoids tend to reflect the ratio K_2O/Na_2O and so commonly are different in the two main alkali olivine basalt series (Fig. 1).

There are a few specialized names that can be used for the feldspathoidal rocks: a nepheline-bearing picrite-basalt is an ankartrite; a nepheline-bearing trachyte is a phonolite; and by definitions given by MacDonald and Katsura (1964, p. 88) an alkali basalt with more than 5% *Ne* containing modal nepheline is a basanite, or if nepheline is not visible, it is a basanitoid. However, for most of the other

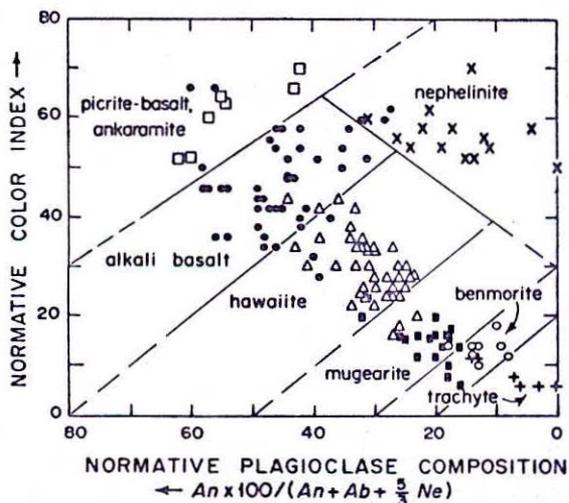


FIG. 10. Plot of normative color index versus normative plagioclase composition for hawaiite - mugearite - benmorite - trachyte suites, showing proposed boundaries for classifying the rocks. A field for nephelinites from Hawaii is also shown. The symbols for the data points are based on the names used by the original authors, and the field boundaries are drawn accordingly. Plots in % cation equivalents.

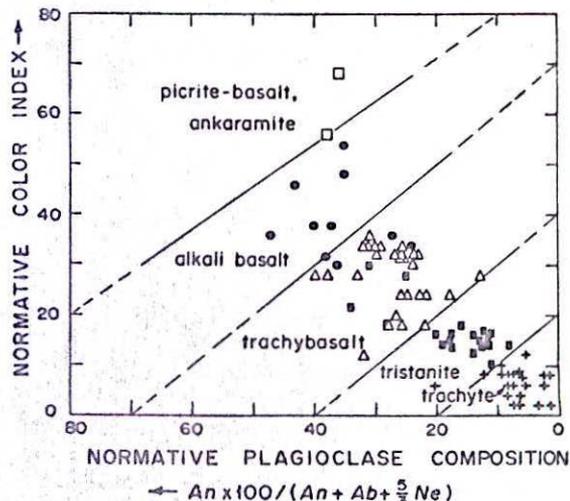


FIG. 11. Plot of normative color index versus normative plagioclase composition for trachybasalt - tristanite - trachyte suites, showing boundaries for classification. Data point symbols based on names used by the original authors. Plots in % cation equivalents.

rocks it seems preferable simply to use the feldspathoid names as varietal modifiers (as in nepheline hawaiite, leucite tristanite, or analcite phonolite). The only modifier we have found in the literature that might be suitable for making the distinction on a purely chemical basis is "critically undersaturated" (Yoder and Tilley 1962), but this is rather lengthy. A handier modifier, if acceptable, might be "sub-silicic".

Coombs and Wilkinson (1969) suggested that alkali olivine basalt series might also be split on the basis of $MgO - FeO - Fe_2O_3$ characteristics, but this possibility will not be pursued here.

Summary

A volcanic rock may be classified on the basis of its chemical composition according to the system depicted in Fig. 1 by proceeding as follows:

1. If the rock has *Ac* in its norm, it is probably peralkaline. Refer to Noble (1968) for a guide to more detailed classification. Otherwise, go to Step 2.
2. Classify as subalkaline or alkaline according to the boundary lines suggested in Figs. 3, 4, and 5. (Fig. 3 is simplest; Fig. 4 is considered most reliable for general purposes; and Fig. 5 may be best

for basalts.) If the rock is subalkaline, go to Step 3; if alkaline, go to Step 4.

3. (a) Classify as calc-alkaline or tholeiitic using the boundary lines in Fig. 2A, B, E, and F, and Fig. 6. (Fig. 2 is considered best for andesites and dacites; Fig. 6, for basalts.)

(b) If *Ol* is greater than 25%, the rock is a picrite basalt. Otherwise classify as basalt, andesite, dacite, or rhyolite according to Fig. 7. More detailed classification as basaltic andesite, high-alumina andesite, or icelandite may be made if appropriate and desirable, as discussed earlier.

(c) Classify as potassium-rich, "average", or potassium-poor according to guidelines such as those suggested in Fig. 8. Go to Step 5.

4.(a) Decide whether the rock is a nephelinite, leucite, or analcite on the basis of its petrographic characteristics and the various chemical criteria mentioned earlier. If it is one of these refer to the references cited for direction to more specific classifications. Otherwise continue below.

(b) Assign the rock to one of the two alkali olivine basalt series on the basis of its K_2O/Na_2O ratio, using Fig. 9. Then classify it according to Fig. 10 or Fig. 11, as appropriate.

5. Check the result against the analyses listed in Appendix II and appropriate comparative analyses from the literature. And most important, check the result against the rock's petrographic characteristics. If the rock has been significantly altered chemically or has some exceptional composition, this step will help to avoid erroneous classification.

Acknowledgment

We would first acknowledge the contributions of Professor Moorehouse. At the time of his death, the report was at a preliminary stage, and he is in no way responsible for its shortcomings. However, several major revisions were made that were a consequence, directly or indirectly, of his attempts to show a better way, and we are most grateful for his efforts. It is perhaps appropriate to take this opportunity to recommend to the reader Professor Moore-

house's paper "A Comparative Atlas of Textures of Archean and Younger Volcanic Rocks," recently published by the Geological Association of Canada (Special Paper No. 8).

We express our appreciation to those who reviewed our preliminary report for their comments and suggestions, and to Mr. H. Klassen, Mr. E. Hsu, and Mr. J. Z. Fraser for assistance in the data compilation. Dr. A. M. Goodwin and Professor H. D. B. Wilson kindly provided copies of unpublished analytical data for use in testing our results; Dr. R. G. Garrett made available a computer plot subroutine.

AMSTUTZ, G. C. 1968. Spilitic and spilite rocks. *In* Basalts. Vol. 2. H. H. Hess and A. Poldervaart (Editors). pp. 737-753. Interscience, John Wiley and Sons, New York. 862 p.

ANDERSON, C. A. 1933. Volcanic history of Glass Mountain, Northern California. *Amer. J. Sci.* 26, pp. 485-506.

——— 1941. Volcanoes of the Medicine Lake highland, California. *Univ. Calif. Bull. Dept. Geol. Sci.* 25, pp. 347-422.

AUMENTO, F. 1968. The Mid-Atlantic ridge near 45° N. II. Basalts from the area of Confederation Peak. *Can. J. Earth Sci.* 5, pp. 1-21.

BAKER, I. 1969. Petrology of the volcanic rocks of Saint Helena Island, South Atlantic. *Bull. Geol. Soc. Amer.* 80, pp. 1283-1310.

BAKER, P. E., GASS, I. G., HARRIS, P. G., and LEMAITRE, R. W. 1964. The volcanological report of the Royal Society expedition to Tristan da Cunha, 1962. *Phil. Trans. Roy. Soc. Lond., Ser. A*, 256, pp. 439-578.

BARAGAR, W. R. A. 1966. Geochemistry of the Yellowknife volcanic rocks. *Can. J. Earth Sci.* 3, pp. 9-30.

——— 1968. Major-element geochemistry of the Noranda Volcanic Belt, Quebec-Ontario. *Can. J. Earth Sci.* 5, pp. 773-790.

——— 1969. Geochemistry of Coppermine River Basalts. *Geol. Surv. Can. Paper* 69-44, 43 p.

BARAGAR, W. R. A. and GOODWIN, A. M. 1969. Andesites and Archean volcanism of the Canadian Shield. *Oreg. Dept. Geol. Miner. Ind., Bull.* 65, pp. 121-141.

BROWN, G. M. 1968. Mineralogy of basaltic rocks. *In* Basalts, Volume 1. H. H. Hess and A. Poldervaart (Editors). pp. 103-162. Interscience, John Wiley and Sons, New York. 482 p.

BYERS, F. M. J. 1959. Geology of Ummak and Bogoslof Islands, Aleutian Islands, Alaska. *U.S. Geol. Surv. Bull.* 1028-L, pp. 267-369.

CARMICHAEL, I. S. E. 1964. The petrology of Thingmuli, a Tertiary volcano in Eastern Iceland. *J. Petrology*, 5, pp. 435-460.

——— 1967. The mineralogy and petrology of the volcanic rocks from Leucite Hills, Wyoming. *Contr. Mineral. Petrology*, 15, pp. 24-66.

- CHAYES, F. 1965. Statistical Petrography. *Carneg. Inst. Wash. Year Book* 64, pp. 153-165.
- . 1966. Alkaline and subalkaline basalts. *Amer. J. Sci.* 264, pp. 128-145.
- . 1969. The chemical composition of Cenozoic andesite. *Oreg. Dept. Geol. Miner. Ind., Bull.* 65, pp. 1-11.
- . 1970. On the amounts of silica and normative quartz in analyses of andesite, dacite, and rhyodacite. *Carneg. Inst. Wash. Year Book* 68, pp. 177-179.
- CHAYES, F. and METAIS, D. 1964. On the relation between suites of CIPW and Barth-Niggli norms. *Carneg. Inst. Wash. Year Book* 63, pp. 193-195.
- COATS, R. R. 1952. Magmatic differentiation in Tertiary and Quaternary volcanic rocks from Adak and Kanaga Islands, Aleutian Islands, Alaska. *Bull. Geol. Soc. Amer.* 63, pp. 485-514.
- . 1953. Geology of Buldir Island, Aleutian Islands, Alaska. *U.S. Geol. Surv. Bull.* 989-A, pp. 1-24.
- . 1956a. Geology of northern Adak Island, Alaska. *U.S. Geol. Surv. Bull.* 1028-C, pp. 45-67.
- . 1956b. Geology of northern Kanaga Island, Alaska. *U.S. Geol. Surv. Bull.* 1028-D, pp. 69-80.
- . 1959. Geologic reconnaissance of Semisopochnoi Island, Western Aleutian Islands, Alaska. *U.S. Geol. Surv. Bull.* 1028-O, pp. 477-519.
- . 1968. Basaltic andesites. *In Basalts*. Volume 2. H. H. Hess and A. Poldervaart (Editors). pp. 689-736. Interscience, John Wiley and Sons, New York. 861 p.
- COATS, R. R., NELSON, W. H., LEWIS, R. Q., and POWERS, H. A. 1961. Geologic reconnaissance of Kiska Island, Aleutian Islands, Alaska. *U.S. Geol. Surv. Bull.* 1028-R, pp. 563-581.
- COOMBS, D. S. 1963. Trends and affinities of basaltic magmas and pyroxenes as illustrated on the diopside - olivine - silica diagram. *Mineral. Soc. Amer. Spec. Paper* 1, pp. 227-250.
- COOMBS, D. S. and WILKINSON, J. F. G. 1969. Lineages and fractionation trends in undersaturated volcanic rocks from the East Otago volcanic province (New Zealand) and related rocks. *J. Petrology*, 10, pp. 440-501.
- COOMBS, H. A. 1939. Mt. Baker, a Cascade volcano. *Bull. Geol. Soc. Amer.* 50, pp. 1493-1510.
- DREWES, H., FRASER, G. S., SNYDER, G. L., and BARNETT, H. F. JR. 1961. Geology of Unalaska Island and Adjacent Insular Shelf, Aleutian Islands, Alaska. *U.S. Geol. Surv. Bull.* 1028-S, pp. 583-676.
- ENGEL, A. E. J., ENGEL, G. G., and HAVENS, R. C. 1965. Chemical characteristics of oceanic basalts and the upper mantle. *Bull. Geol. Soc. Amer.* 76, pp. 719-734.
- FISKE, R. S., HOPSON, C. A., and WATERS, A. C. 1963. Geology of Mt. Ranier National Park, Washington. *U.S. Geol. Surv. Prof. Paper* 444, pp. 1-93.
- FRASER, G. D. and BARNETT, H. F. 1959. Geology of the Delarof and Westernmost Andreanof Islands, Aleutian Islands, Alaska. *U.S. Geol. Surv. Bull.* 1028-I, pp. 211-248.
- GOODWIN, A. M. 1967. Volcanic studies in the Birch-Uchi Lakes area of Ontario. *Ont. Dept. Mines Miscellaneous Paper* 6, 96 p.
- HIGGINS, M. W. and WATERS, A. C. 1968. Newberry Caldera field trip. *Oreg. Dept. Geol. Miner. Ind. Bull.* 62, pp. 59-77.
- HOLMES, A. 1920. The nomenclature of petrology. Murby, London. 284 p.
- JOHANNSEN, A. 1939. A descriptive petrography of igneous rocks. Volume 1, 2nd ed., Univ. Chicago Press, Chicago. 318 p.
- KENNEDY, W. Q. 1933. Trends of differentiation in basaltic magmas. *Amer. J. Sci. Ser. 5*, 25, pp. 239-256.
- KUNO, H. 1959. Origin of Cenozoic petrographic provinces of Japan and surrounding areas. *Bull. Volcanologique, Series II*, 20, pp. 37-76.
- . 1960. High-alumina basalt. *J. Petrology*, 1, pp. 121-145.
- KUNO, H. 1966. Lateral variation of basalt magma across continental margins and island arcs. *Geol. Surv. Can. Paper* 66-15, pp. 317-336.
- . 1968. Differentiation of basalt magmas. *In Basalts*, Volume 2. H. H. Hess and A. Poldervaart (Editors). pp. 623-688. Interscience, John Wiley and Sons, New York. 862 p.
- LEMAITRE, R. W. 1962. Petrology of volcanic rocks, Gough Island, South Atlantic. *Bull. Geol. Soc.* 73, pp. 1309-1340.
- MACDONALD, G. A. 1949a. Petrography of the island of Hawaii. *U.S. Geol. Surv. Prof. Paper* 214-D, pp. 51-96.
- . 1949b. Hawaiian Petrographic Province. *Bull. Geol. Soc. Amer.* 60, pp. 1541-1596.
- . 1968. Composition and origin of Hawaiian lavas. *Geol. Soc. Amer. Mem.* 116, pp. 477-522.
- MACDONALD, G. A. and POWERS, H. A. 1946. Contribution to the petrography of Haleakala Volcano, Hawaii. *Bull. Geol. Soc. Amer.* 57, pp. 115-124.
- MACDONALD, G. A. and EATON, J. P. 1955. Hawaiian Volcanoes during 1953. *U.S. Geol. Surv. Bull.* 1021-D, pp. 127-166.
- MACDONALD, G. A. and KATSURA, T. 1961. Variations in the lava of the 1959 eruption in Kilauea Iki. *Pacific Sci.* 15, pp. 358-369.
- . 1964. Chemical composition of Hawaiian lavas. *J. Petrology*, 5, pp. 82-133.
- MCBIRNEY, A. R. 1968a. Compositional variations of the climatic eruption of Mt. Mazama. *Oreg. Dept. Geol. Miner. Ind. Bull.* 62, pp. 53-57.
- . 1968b. Petrochemistry of the Cascade andesite volcanoes. *Oreg. Dept. Geol. Miner. Ind. Bull.* 62, pp. 101-107.
- . 1969. Andesitic and rhyolitic volcanism of orogenic belts. *Amer. Geoph. Union Monograph* 13, pp. 501-507.
- MCBIRNEY, A. R. and AOKI, K. 1968. Petrology of the island of Tahiti. *Geol. Soc. Amer. Mem.* 116, pp. 523-556.
- MIYASHIRO, A. 1968. Metamorphism of mafic rocks.

- In Basalts*, Volume 2. H. H. Hess and A. Poldervaart (Editors). pp. 799-834. Interscience, John Wiley and Sons, New York. 862 p.
- MOORE, J. G. 1965. Petrology of deep-sea basalt near Hawaii. *Amer. J. Sci.* 263, pp. 40-52.
- MUIR, I. D. and TILLEY, C. E. 1961. Mugearites and their place in alkali igneous rock series. *J. Geol.* 69, pp. 186-203.
- 1963. Contributions to the petrology of Hawaiian Basalts. 2. The tholeiitic basalts of Mauna Loa and Kilauea. *Amer. J. Sci.* 261, pp. 111-128.
- 1964. Basalts from the northern part of the rift zone of the Mid-Atlantic Ridge. *J. Petrology*, 5, pp. 409-434.
- 1966. Basalts from the northern part of the Mid-Atlantic ridge. II. The Atlantic collection near 30° N. *J. Petrology*, 1, pp. 193-201.
- MUIR, I. D., TILLEY, C. E., and SCOON, J. H. 1957. Contributions to the petrology of Hawaiian basalts. I. The picrite-basalts of Kilauea. *Amer. J. Sci.* 255, pp. 241-253.
- MURATA, K. J. and RICHTER, D. H. 1961. Magmatic differentiation in the Uwekahuna Laccolith, Kilauea Caldera, Hawaii. *J. Petrology*, 2, pp. 424-447.
- 1966. Chemistry of lavas of the 1959-60 eruption of Kilauea Volcano, Hawaii. *U.S. Geol. Surv., Prof. Paper* 537-A, 26 p.
- NELSON, W. H. 1959. Geology of Segula, Davidof and Khvostof Islands, Alaska. *U.S. Geol. Surv., Bull.* 1028-K, pp. 257-266.
- NICHOLLS, G. D. 1965. Basalts from the deep ocean floor. *Mineral. Mag.* 34, pp. 373-388.
- NOBLE, D. C. 1968. Systematic variation of major elements in commendite and pantellerite glasses. *Earth Planet. Sci. Letters*, 4, pp. 167-172.
- NOCKOLDS, S. R. and ALLEN, R. 1953. The geochemistry of some igneous rock series. *Geoch. et Cosmochim. Acta*, 4, pp. 105-142.
- PEACOCK, M. A. 1931. Classification of igneous rocks. *J. Geol.* 39, pp. 54-67.
- POLDERVAART, A. 1962. Aspects of basalt petrology. *J. Geol. Soc. India* 3, pp. 1-14.
- 1964. Chemical definition of alkali basalts and tholeiites. *Bull. Geol. Soc. Amer.* 75, pp. 229-232.
- POWERS, H. A., COATES, R. R., and NELSON, W. H. 1960. Geology and submarine physiography of Amchitka Island, Alaska. *U.S. Geol. Surv. Bull.* 1028-P, pp. 521-554.
- RICHTER, D. H., AULT, W. U., EATON, J. P., and MOORE, J. G. 1964. The 1961 eruption of Kilauea Volcano, Hawaii. *U.S. Geol. Surv. Prof. Paper* 474-D, 34 p.
- SHAND, H. S. 1951. *Eruptive rocks*. 4th ed., John Wiley and Sons, New York. 488 p.
- SIMMONS, F. S. and MATHEWSON, D. E. 1955. Geology of Great Sitkin Island, Alaska. *U.S. Geol. Surv. Bull.* 1028-B, pp. 21-43.
- SMITH, A. L. and CARMICHAEL, I. S. E. 1968. Quaternary lavas from the southern Cascades, Western U.S.A. *Contr. Mineral. Petrol.* 19, pp. 212-238.
- SNYDER, G. L. 1959. Geology of Little Sitkin Island, Alaska. *U.S. Geol. Surv. Bull.* 1028-H, pp. 169-210.
- SWANSON, D. A. 1967. Yakima basalt of the Tieton River area, south-central Washington. *Bull. Geol. Soc. Amer.* 78, pp. 1077-1110.
- THAYER, T. P. 1937. Petrology of later Tertiary and Quaternary rocks of the north-central Cascade Mountains in Oregon, with notes on similar rocks in western Nevada. *Bull. Geol. Soc. Amer.* 48, pp. 1611-1652.
- TILLEY, C. E. 1950. Some aspects of magmatic evolution. *Quart. J. Geol. Soc. Lond.* 106, pp. 37-61.
- 1960a. Kilauea magma 1959-60. *Geol. Mag.* 97, pp. 434-497.
- 1960b. Differentiation of Hawaiian basalts. Some variants in lava suites of dated Kilauea eruptions. *J. Petrology*, 1, pp. 47-55.
- TILLEY, C. E. and MUIR, I. D. 1964. Intermediate members of the oceanic basalt-trachyte association. *Geol. Foren. Stockholm Forh.* 85, pp. 434-443.
- 1967. Tholeiite and tholeiitic series. *Geol. Mag.* 104, pp. 337-343.
- TILLEY, C. E. and SCOON, J. H. 1961. Differentiation of Hawaiian basalts: Trends of Mauna Loa and Kilauea historic magma. *Amer. J. Sci.* 259, pp. 60-68.
- VALLANCE, T. G. 1960. Concerning spilites. *Proc. Linn. Soc. N.S.W.*, 85, pp. 8-52.
- 1965. On the chemistry of pillow lavas and the origin of spilites. *Mineralog. Mag.* 34, pp. 471-481.
- VERHOOGEN, J. 1937. Mt. St. Helens: a recent Cascade Volcano. *Univ. Calif. Publ. Geol. Sci.* 24, pp. 262-301.
- WAGER, L. R. and DEER, W. A. 1939. The petrology of the Skaergaard intrusion, Kangerdlugssuag, East Greenland. *Meddl. om Grønland*, 105, No. 4, pp. 1-352.
- WASHINGTON, H. S. 1906. The Roman comagmatic region. *Carneg. Inst. Wash. Publ.* 57, 199 p.
- WATERS, A. C. 1961. Stratigraphic and lithologic variations in the Columbia River basalt. *Amer. J. Sci.* 259, pp. 583-611.
- 1962. Basalt magma types and their tectonic association: Pacific Northwest of the United States. *Amer. Geophys. Union Monograph* 6, pp. 158-170.
- WILCOX, R. E. 1954. Petrology of Paricutin Volcano, Mexico. *U.S. Geol. Surv., Bull.* 965-C, pp. 281-353.
- WILKINSON, J. F. G. 1968a. The petrography of basaltic rocks. *In Basalts*, Volume 1. H. H. Hess and A. Poldervaart (Editors). pp. 163-214. Interscience, John Wiley and Sons, New York. 862 p.
- 1968b. Analcimes from some potassic igneous rocks and aspects of analcime-rich igneous assemblages. *Contrib. Mineral. Petrology*, 18, pp. 252-269.
- WILLIAMS, H. 1932. Geology of the Lassen Volcanic National Park, California. *Univ. Calif. Bull. Dept. Geol. Sci.* 21, pp. 195-385.
- 1934. Mt. Shasta, California. *Zeitschrift Fur*

- Vulkanologie, 15, pp. 225-253.
- 1935. Newberry Volcano of central Oregon. Bull. Geol. Soc. Amer. 46, pp. 253-304.
- 1942. The geology of Crater Lake National Park, Oregon. Carneg. Inst. Wash. Publ. 540, 162 p.
- 1950. Volcanoes of the Paricutin region, Mexico. U.S. Geol. Surv. Bull. 965-B, pp. 165-279.
- WILLIAMS, H., TURNER, F. J., and GILBERT, C. H. 1954. Petrography. Freeman and Co., San Francisco. 406 p.
- WILSON, H. D. B., ANDREWS, P., MOXHAM, R. L., and RAMLAL, K. 1965. Archean volcanism of the Canadian Shield. Can. J. Earth Sci. 2, pp. 161-175.
- WINCHELL, H. 1947. Honolulu series, Oahu, Hawaii. Bull. Geol. Soc. Amer. 58, pp. 1-48.
- WISE, W. S. 1969. Geology and petrology of the Mt. Hood area: a study of High Cascade volcanism. Bull. Geol. Soc. Amer. 80, No. 6, pp. 969-1006.
- YODER, H. S. and TILLEY, C. E. 1962. Origin of basalt magmas: an experimental study of natural and synthetic rock systems. J. Petrology, 3, pp. 342-532.
- Donald and Powers 1946; Muir and Tilley 1961.
- Hawaiian nephelinitic rocks:*
MacDonald 1968; Winchell 1947.
- Hawaiian tholeiitic rocks:*
MacDonald 1949a, 1949b, 1968; MacDonald and Eaton 1955; MacDonald and Katsura 1961, 1964; Moore 1965; Muir and Tilley 1963, 1964; Muir *et al.* 1957; Murata and Richter 1961, 1966; Richter *et al.* 1964; Tilley 1960a, 1960b; Tilley and Scoon 1961.
- Mid-Atlantic tholeiitic rocks:*
Aumento 1968; Muir and Tilley 1964, 1966; Nichols 1965.
- Mount Hood area, Washington:*
Wise 1969. This group of data comprises 140 analyses of extrusive rocks. In Figs. 2, 3, 4, 6 and 8 the distribution of the data points has been indicated by two solid-line "contours": the inner line encloses the main cluster of points, generally encompassing about 90% of the analyses; the outer line encloses all points, including the more scattered ones. In Fig. 7, the rocks are classified as in the unpublished appendix to Wise's paper.
- Noranda volcanic belt:*
Baragar 1968.
- Other Superior Province volcanic belts:*
Goodwin 1967; Wilson *et al.* 1965; and unpublished data supplied by these authors.
- Paricutin region, Mexico:*
Wilcox 1954; Williams 1950.
- Saint Helena Island:*
Baker 1969.
- Tahiti Island:*
McBirney and Aoki 1968.
- Thingmuli Volcano, Iceland:*
Carmichael 1964.
- Tristan da Cunha:*
Baker *et al.* 1964.
- Yellowknife volcanic belt:*
Baragar 1966.
- Hawaiite - Mugearite - Benmorite - Trachyte Series:*
MacDonald 1949a, 1949b, 1968; MacDonald and Katsura 1964; Muir and Tilley 1961.
- Trachybasalt - Tristanite - Trachyte Series:*
Baker *et al.* 1964; LeMaitre 1962.

Appendix I

Sources of Data for the Various Suites and Groupings of Rocks Plotted in Figs. 2-12, with Explanatory Notes

Aleutian Islands, Alaska:

Byers 1959; Coats 1952, 1953, 1956a, 1956b, 1959; Coats *et al.* 1961; Drewes *et al.* 1961; Fraser and Barnett 1959; Nelson 1959; Powers *et al.* 1960; Simmons and Mathewson 1955; Snyder 1959.

Cascade Volcanoes, California, Oregon, and Washington:

Anderson 1933, 1941; Coombs 1939; Fiske *et al.* 1963; Higgins and Waters 1968; McBirney 1968a, 1968b; Smith and Carmichael 1968; Thayer 1937; Verhoogen 1937; Williams 1932, 1934, 1935, 1942.

Columbia River Basalts:

Swanson 1967; Waters 1961, 1962; Wise 1969.

Coppermine River Basalts:

Baragar 1969.

Gough Island:

LeMaitre 1969.

Hawaiian Alkalic Rocks:

MacDonald 1949a, 1949b, 1968; MacDonald and Katsura 1961, 1964; Mac-

Table of typical analyses of each of the main rock types listed in Fig. 1

Entry*	Subalkaline rocks										Peralkaline rocks		Alkaline rocks														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Series	Tholeiitic basalt series					Calc-alkali series					Alkali olivine basalt series												Nephelinites, etc.				
Type of rock	Tholeiitic picrite-basalt	Olivine tholeiite	Tholeiite	Tholeiitic andesite	Icelandite	High-alumina basalt	High-alumina andesite	Andesite	Dacite	Rhyolite	Pantellerite	Commendite	Alkalic picrite-basalt	Ankararite	"K-poor" alkali olivine basalt	"K-rich" alkali olivine basalt	Trachybasalt	Hawaiite	Mugearite	Tristanite	Beaumontite	Trachyte	Phonolite	Nephelinite	Analcite	Leucite	Wyomingite
SiO ₂	46.4	49.16	53.8	58.31	61.76	49.15	58.65	60.0	69.68	73.23	69.80	75.23	46.57	44.1	45.4	42.43	46.48	47.9	49.68	55.85	55.64	60.7	60.64	39.7	49.0	46.24	54.09
Al ₂ O ₃	8.5	13.33	13.9	13.77	15.36	17.73	17.43	16.0	15.21	14.03	7.40	11.99	8.20	12.1	14.7	14.15	16.68	15.9	16.99	18.98	16.38	20.5	18.29	11.4	13.0	14.42	9.94
Fe ₂ O ₃	2.5	1.31	2.6	3.37	2.35	2.76	3.21	1.89	1.08	0.60	2.42	0.90	1.20	3.2	4.1	5.84	4.12	4.9	3.45	2.59	3.05	2.3	2.75	5.3	4.9	4.06	3.15
MgO	9.8	9.71	9.3	6.48	5.84	7.20	3.48	6.20	1.90	1.70	6.15	1.25	9.75	9.6	9.2	8.48	7.30	7.6	8.99	3.11	4.91	0.4	1.18	8.2	4.5	4.36	1.48
MnO	20.8	10.41	4.1	2.27	1.76	6.91	3.28	3.90	0.91	0.35	0.05	0.02	19.65	13.0	7.8	6.71	4.65	4.8	2.79	2.04	1.06	0.2	0.09	12.1	8.3	6.99	6.99
CaO	7.4	10.93	7.9	5.58	5.04	9.91	6.26	5.87	2.70	1.32	0.45	0.27	9.43	11.5	10.5	11.91	9.40	8.0	5.46	4.51	2.90	1.4	0.83	12.8	11.5	13.24	4.71
Na ₂ O	1.6	2.15	3.0	3.91	4.37	2.88	3.82	3.85	4.47	3.94	6.70	4.79	1.56	1.9	3.0	2.77	3.80	4.2	5.78	5.16	6.07	6.2	8.93	3.8	3.9	1.65	1.36
K ₂ O	0.3	0.51	1.5	1.88	1.62	0.72	1.99	0.87	3.01	4.08	4.30	4.67	1.18	0.7	1.0	2.04	3.07	1.5	1.90	4.08	3.49	6.7	5.10	1.2	3.0	6.37	11.38
TiO ₂	2.0	2.29	2.0	1.71	1.27	1.52	0.79	1.04	0.36	0.24	0.45	0.13	1.85	2.7	3.0	4.11	3.10	3.4	2.13	1.80	0.89	0.5	0.04	2.8	0.7	1.17	2.35
P ₂ O ₅	0.2	0.16	0.4	0.46	0.44	0.26	0.18	0.23	0.10	0.05	0.15	0.09	0.26	0.3	0.4	0.58	0.90	0.7	0.48	0.39	0.66	0.03	—	0.9	1.1	0.41	1.79
MnO	0.2	0.16	0.2	0.23	0.19	0.14	0.10	0.16	0.04	0.02	0.32	0.08	0.14	0.2	0.2	0.17	0.18	0.2	0.27	0.12	0.18	0.2	0.23	0.2	0.1	—	0.08

*Notes to Appendix II.

1. Average Hawaiian tholeiitic picrite-basalt (oceanite). MacDonald (1968), Table 8.
2. Olivine tholeiite, Kilauea volcano, Hawaii. Yoder and Tilley (1962), Table 2, entry 14.
3. Average Yakima-type tholeiite, Columbia River basalt. Waters (1962), Table 2.
4. Average iron-rich andesite from oceanic and non-orogenic regions. McBirney (1969), Table 2.
5. Icelandite, Thingmuli volcano, Iceland. Carmichael (1964), Table 9, entry 14.
6. Average high-alumina basalt, Cascades, and Oregon Plateau. Waters (1962), Table 3.
7. Average calc-alkali andesite from continental margins. McBirney (1969), Table 2.
8. Average andesite from 4 Archean volcanic belts, recalculated to 100% without H₂O, CO₂. Baragar and Goodwin (1969), Table III.
9. Average dacite, Cascade volcanoes. Carmichael (1964), Table 8.
10. Average rhyolite, Cascade volcanoes. Carmichael (1964), Table 8.
11. Pantellerite glass, Island of Pantelleria. Noble (1968), Table 1, entry 7. Analysis also shows: ZrO₂, 0.35; Cl, 0.90; F, 0.36.
12. Commendite glass, Thirsty Canyon Tuff. Noble (1968), Table 1, entry 2. Analysis also shows: ZrO₂, 0.09; Cl, 0.18; F, 0.25.
13. Picrite basalt, Gough Island. Lemaitre (1962), Table 10, sample G121.
14. Average Hawaiian Ankararite. MacDonald (1968), Table 8.
15. Average Hawaiian alkali olivine basalt. MacDonald (1968), Table 8.
16. Alkali olivine basalt, Tristan da Cunha. Baker *et al.* (1964), Table 6, sample 6.
17. Trachybasalt lava, Tristan da Cunha. Baker *et al.* (1964), Table 6, sample 20.
18. Average Hawaiian hawaiite. MacDonald (1968), Table 8.
19. Mugearite, from near Mugear, Skye. Muir and Tilley (1961), Table 4, entry 1.
20. Average of 3 tristanites from Tristan da Cunha. Tilley and Muir (1964), Table 1, entry 1.
21. Beaumontite, Hebridean Series, Skye. Tilley and Muir (1964), Table 1, entry 3.
22. Alkali feldspar trachyte, Tristan da Cunha. Baker *et al.* (1964), Table 6, sample 31.
23. Phonolite dike, St. Helena Island. Baker (1969), Table 2, sample 403.
24. Average Hawaiian nephelinite. MacDonald (1968), Table 8.
25. Average of 4 analcites (analcimites) from the Highwood Mountains, Montana. Wilkinson (1968), Table 4, entry 1.
26. Leucite, Roman magmatic province, Washington (1906), p. 131.
27. Average Wyomingite, Leucite Hills, Wyoming. Carmichael (1967), Table 16, entry 6.

Appendix III

Equations or Inequalities that will Enable Classification of a Volcanic Rock in a Computer Program

Symbols:

$S = \text{SiO}_2$, wt %	CI = color index, cation norm
$A = \text{Na}_2\text{O} + \text{K}_2\text{O}$, wt %	$P = 100 An/(An + Ab)$, cation norm
$F = \text{FeO} + 0.8998 \text{Fe}_2\text{O}_3$, wt %	Ol = olivine, cation norm
$M = \text{MgO}$, wt %	X = percentage in a ternary plot.

FIG. 2. Tholeiitic vs. calc-alkaline rocks.

The rock is tholeiitic if

$$X_F \geq (1.5559 \times 10^{-12})X_M^8 - (7.7142 \times 10^{-10})X_M^7 + (1.5664 \times 10^{-7})X_M^6 - (1.6738 \times 10^{-5})X_M^5 + (1.0017 \times 10^{-3})X_M^4 - (3.2552 \times 10^{-2})X_M^3 + (4.7776 \times 10^{-1})X_M^2 - 1.1085X_M + 30.0$$

where $P < 40$

given $X_A + X_F + X_M = 100$

FIG. 3. Alkaline vs. subalkaline rocks.

The rock is subalkaline if

$$S \geq -(3.3539 \times 10^{-4})A^6 + (1.2030 \times 10^{-2})A^5 - (1.5188 \times 10^{-1})A^4 + (8.6096 \times 10^{-1})A^3 - 2.1111A^2 + 3.9492A + 39.0$$

FIG. 4. Alkaline vs. subalkaline rocks.

The rock is subalkaline if

$$X_{Ne'} \leq 1.5X_{Q'}, \text{ where } X_{Ol'} = 40-100$$

or if

$$X_{Ne'} < 15 + 0.8889 X_{Q'}, \text{ where } X_{Ol'} = 0-40$$

given $X_{Ol'} + X_{Ne'} + X_{Q'} = 100$

FIG. 6. Calc-alkaline vs. tholeiitic rocks.

The rock is calc-alkaline if

$$\text{Al}_2\text{O}_3 \geq 12 + 0.08 P, \text{ where } P = 40-100$$

FIG. 7. Classification of subalkaline rocks.

Examined in the following sequence of tests, a subalkaline rock is

- (a) picrite basalt if $Ol \geq 25$
- (b) basalt if $CI \geq 70 - P$
- (c) andesite if $CI \geq 30 - \frac{1}{3}P$
- (d) dacite if $CI \geq 20 - P$
- (e) rhyolite if $CI < 20 - P$

FIG. 8. Further classification of subalkaline rocks.

The rock is "K-rich" if

$$X_{Ab'} \leq -(1.3482 \times 10^{-6})X_{Or}^6 + (2.1157 \times 10^{-4})X_{Or}^5 - (1.2000 \times 10^{-2})X_{Or}^4 + (3.0554 \times 10^{-1})X_{Or}^3 - 3.6890 X_{Or}^2 + 20.4400 X_{Or} - .35$$

The rock is "K-poor" if

$$X_{Ab'} \geq -(1.8496 \times 10^{-6})X_{Or}^6 + (2.1187 \times 10^{-4})X_{Or}^5 - (9.3497 \times 10^{-3})X_{Or}^4 + (2.0202 \times 10^{-1})X_{Or}^3 - 2.2698 X_{Or}^2 + 13.4379 X_{Or} + 20.2$$

Otherwise it is "average".

$$X_{Or} + X_{Ab} + X_{An} = 100$$

FIG. 9. Separation of alkali olivine basalt series.

The rock is in the "sodic" series if

$$X_{Ab'} \geq (1.3162 \times 10^{-5}) X_{Or}^6 - (1.3525 \times 10^{-3}) X_{Or}^5 + (5.3479 \times 10^{-2}) X_{Or}^4 - 1.0154 X_{Or}^3 + 9.2090 X_{Or}^2 - 28.6217 X_{Or}$$

given $X_{Or} + X_{Ab'} + X_{An'} = 100$

FIG. 10. Classification of the sodic alkali olivine basalt series.

Examined on the following sequence of tests, the rock is:

- (a) picrite basalt if $Ol \geq 25\%$
- (b) ankaramite if $CI \geq 30 + \frac{5}{8}(80 - P)$
- (c) nephelinite if $CI \geq 30 + \frac{5}{8}P$
- (d) alkali basalt if $CI \geq 80 - P$
- (e) hawaiiite if $CI \geq 50 - P$
- (f) mugearite if $CI \geq 30 - P$
- (g) benmorite if $CI \geq 20 - P$
- (h) sodic trachyte if $CI < 20 - P$

FIG. 11. Classification of the potassic alkali olivine basalt series.

Examined in the following sequence of tests, the rock is:

- (a) picrite basalt if $Ol \geq 25\%$
- (b) ankaramite if $CI \geq 20 + \frac{4}{9}(80 - P)$
- (c) alkali basalt if $CI \geq 70 - P$
- (d) trachybasalt if $CI \geq 40 - P$
- (e) tristanite if $CI \geq 20 - P$
- (f) trachyte if $CI < 20 - P$

