On the delimitation of diorite and gabbro and related rocks.

(With Plate XXV.)

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THERE is general agreement as to the basis on which most major igneous rock-types are defined despite some difference of opinion as to quantitative limits. This is not true of diorites and gabbros (or of their hypabyssal and volcanic equivalents) in distinguishing between which at least four different criteria are in current use.

At the beginning of the microscope era, Zirkel (1866) and Rosenbusch (1877) defined diorite and gabbro as plagioclase-felspar-rocks with hornblende and/or biotite, and with pyroxene, respectively, and this criterion is still used in Harker's 'Petrology for students'. Because the more basic hornblende-diorites, so defined, are chemically indistinguishable from gabbros, and because their hornblende is often altered pyroxene, Rosenbusch (1907, p. 263) later re-defined diorite and gabbro on the basis of their plagioclase-felspars, that of diorites having less, and that of gabbros more, than 50 % of anorthite. It is doubtful whether he meant this distinction to be rigidly applied, but subsequent authorities basing their definitions of types on the composition of the felspar (e.g. Johannsen, Holmes, and Niggli) have so used it. Tröger (1935) created a group of gabbro-diorites for rocks characterized by andesine-labradorite; this corresponds to the belugite family of Spurr (1898).

A number of writers have recently abandoned the felspar criterion in favour of one based on colour-index, probably because (*a*) in the andesites much of the felspar is often occult in the residual glass, and is more sodic than that actually developed, so that the average composition of the felspar cannot be modally determined, and (*b*) because the darker diorites, so defined as having oligoclase or andesine as dominant felspar, are chemically gabbroic (hence Barrell's dictum, quoted by Shand (1927, p. 184), that no rock with a considerable proportion of dark minerals should be called 'diorite'). Such writers define diorite as leucocratic (or felsic) and gabbro as mesotype to melanocratic (mafelsic or mafic), although they do not agree on the quantitative definition of these terms. Shand's boundary (1927, pp. 132, 184; 1939, pp. 196, 281) is 30 % by volume, Lacroix's (1933, pp. 24, 192–3) 35 % by weight, Washington's (1923, p. 569)—for andesite and basalt—37·5 % by weight. E. Wenk (1946) has also recently gone on record in favour of a colour-index boundary between andesite and basalt, but without specifying an exact figure. Shand also uses the felspar criterion to distinguish between soda- and lime-diorites and soda- and lime-gabbros, while Johannsen also uses a colour-index boundary of 50 to mark off meladiorites and mela-gabbros. Later, Johannsen (1939, preface) has stated that he has considered substituting colour-index divisions of 10–40–70 for those of 5–50–95 used in his classification, although he gives no reason for this. Statistical evidence will be given in its favour later in this paper.

In addition to modal criteria, there are others based on chemical analysis; thus for glassy and merocrystalline rocks Lacroix uses the normative colour-index, defining andesites as belonging to class II and basalts to class III of the C.I.P.W. (Cross, Iddings, Pirsson, and Washington) system. Hatch and Wells, adapting the less rigid scheme of Brögger (1895), use a silica percentage of 55 (1937) or 52 (1926). Such definitions are of little use petrographically since they necessitate either a chemical analysis or an accurate mineralogical analysis combined with a chemical analysis of the constituent minerals, and this is impracticable except for a relatively small number of rocks.

For dealing with large series of rock specimens, types must if possible be defined in such a way that rocks can be named readily with a recourse to no more than thin-section or immersion micro-technique, yet so that chemically as well as mineralogically similar rocks are on the whole grouped together. In the framing of such a definition, boundaries should be selected so as to coincide as far as possible with minima in the frequency-distribution of rocks with relation to the chosen criteria. If such minima exist there will also be maxima which will correspond to real objective types. The investigation here recorded had as its object the establishment of such boundaries and types by the study of the frequency-distribution of actual rocks along co-ordinates representing the three main characters used in defining diorites and gabbros. Where no such boundaries can be shown to exist and it is still desired to divide a series into two or more types, the boundary selected may coincide with some chemical relationship or be a matter of practical convenience; if possible, both.

All the definitions of diorite and gabbro which have been quoted are claimed by their authors to include the more typical examples. Combining them, it appears that typical diorites are rocks in which oligoclase or andesine is dominant and hornblende with or without biotite is subordinate in amount, while typical gabbros are rocks with labradorite or bytownite and a pyroxene in roughly equal proportions. If the anorthosites are also included, as rocks composed entirely or almost entirely of a lime-soda-plagioclase, we have the following tabular arrangement of types:

TABLE I.

Ferromagnesian minerals.	More sodic felspars.	More calcic felspars.
About equal to quartz and felspar (mafelsic) or predominant (mafic)	Mafelsic and mafic diorites or soda-gabbros	*Typical gabbros* and norites (mainly pyroxene-rocks), with some hornblende-rocks (hornblende-gabbros)
Definitely subordinate to quartz and felspar, but nevertheless essential (felsic)	*Typical diorites* (mainly hornblende and/or biotite rocks, with some pyroxene rocks (augite-diorites, &c.)	Felsic gabbros or lime diorites
Absent, accessory, or very minor in amount (holofelsic)	Holofelsic diorites or soda-anorthosites	*Anorthosites*

(The terms felsic, mafelsic, and mafic are here used qualitatively, as by Tyrrell in his 'Principles of petrology' (1926). They seem more satisfactory than the terms leucocratic, mesotype, and melanocratic, which have been given several quantitative meanings.)

The problem is that of deciding the appropriate quantitative values of the boundaries in this table, and also of correctly placing the mafelsic and mafic diorites and felsic gabbros. To do this, an attempt has been made to collect a random sample of rock modes within the limits of the field, excluding over-saturated rocks (limit, 10 % of quartz) and under-saturated (limit, $2\frac{1}{2}$ % of olivine and any felspathoid), and including only rocks with at least $\frac{2}{3}$ of the felspar as plagioclase (ranging in composition from An_{20} to An_{80}) and with up to 80 % of mafic minerals. Modes within these limits have been collected from all available literature. Gravimetric modes have been converted to volumetric, because the latter determine the visible character of rocks. Many authors publish modes without stating whether they are by weight or volume, and it has been necessary to decide this in many cases by indirect evidence. Such authors appear to think that the difference between percentages by weight and volume is insignificant; this may be true of rocks near the ends of the colour-index range, but for those with between 25 % and

75 % of dark minerals the difference may be anything from 4 % to 8 %, or even more if much iron ore is present.

The number of published modes being considered inadequate, as many rocks as possible in the British Museum collection, falling within the chosen limits, have been micrometrically analysed by means of the Leitz integrating stage, the composition of the felspar being determined by extinction methods, as these are likely to continue in use for ordinary determinative work on account of their speed and convenience. The average composition of zoned felspars was arrived at by estimating the composition and relative volume of the kernel and successive concentric shells of typical crystals. It is safe to say that by adding this set of data to that obtained from the literature a roughly representative sample of the saturated plagioclase-rocks has been obtained, although the total number (about 400 plutonic rocks) is, even so, smaller than is desirable. Similar (but scantier) data have been amassed for the hypabyssal and volcanic rocks, which will be considered after the diorites and gabbros.

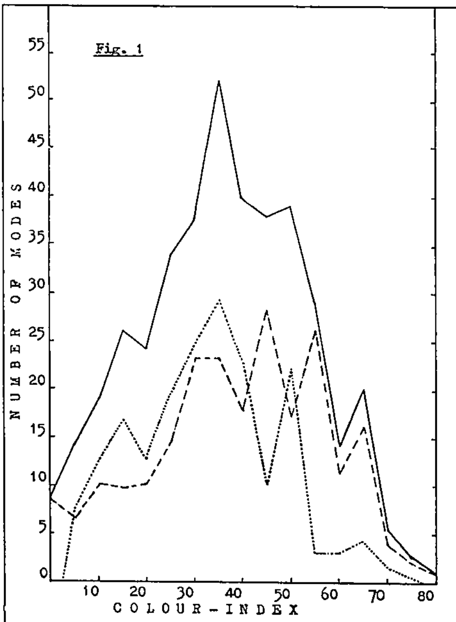
The data have been ranged in three series of subgroups according to the values of the three principal modal characters used as criteria, namely, (1) colour-index (volumetric percentage of dark minerals), (2) percentage of anorthite in the plagioclase, and (3) ratio of pyroxene to hornblende and biotite.

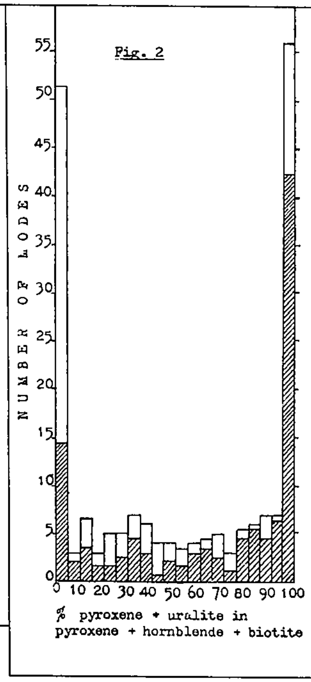
Fig. 1 shows the 418 modes in which the colour-index is known, approximated to the nearest 5 % and arranged as a frequency diagram. The distribution is also shown separately for rocks with oligoclase or andesine (Ab $>$ An), and with labradorite or bytownite (An $\geqslant$ Ab). The main diagram shows a fairly symmetrical distribution with a maximum at 35 and a range of 0–70, above which there are very few modes. The rocks with oligoclase and andesine also show a maximum value at 35, but are deeply divided at a value of 45 between this maximum and a secondary peak at 50, above which there is a very rapid falling off. Those with labradorite and bytownite, the bulk of which range from 30 to 65 (i.e. 28–67) are divided less deeply, but in three places. That at 40 appears to be the most significant of these, since it corresponds to a similar point in the labradorite- and bytownite-bearing dike rocks and lavas (figs. 11, 13); it divides the series into two nearly equal portions. This suggests the possible existence of felsic and mafelsic natural groups, the boundary between which is at a slightly higher colour-index for rocks richer in soda-felspar.

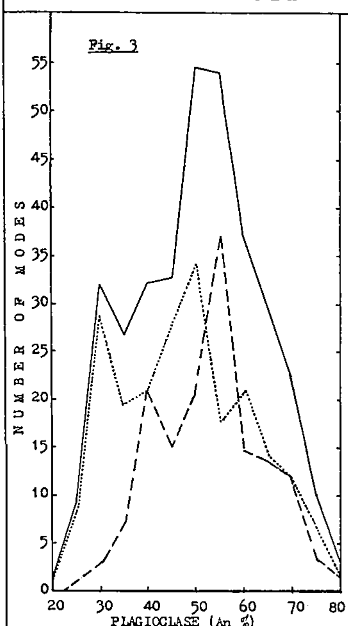
Fig. 2 shows the 362 modes in which the composition of the plagioclase is known (in 66 cases it is given as simply andesine, labradorite, &c.),

similarly arranged, rocks with colour-index values of less and more than 40 being also shown separately. No fewer than 55 rocks (about one-seventh) have plagioclase approximating to An_{50} in composition, this being actually the commonest value. This is partly because modes in which the felspar is described as andesine-labradorite have all been given this value (a similar explanation certainly accounts for the peak at oligoclase-andesine, An_{30}) but it is too marked a feature to be mainly explained away in this manner. This is true also for the felsic series considered separately: in this case there is a rapid decrease in numbers between An_{50} and An_{55}. The mafelsic series (colour-index > 40) has a maximum at An_{55} and falls away steeply and fairly symmetrically on both sides of this; there is a minor peak at An_{40}. This suggests that the An_{50} line is not a satisfactory boundary between major types, although one drawn between An_{50} and An_{45} might be so, especially for mafelsic types. It may be noted that a molecular proportion of 48 % of anorthite is equivalent to 50 % by weight; also that Holmes (1917) suggested that An_{47} would be a more convenient boundary than An_{50}, since it falls near the boundary between orders 3 and 4 in the C.I.P.W. system.

Fig. 3 shows all the data grouped at 10 % intervals according to the percentage of pyroxene + uralitic amphibole in pyroxene + hornblende + biotite. This indicates a marked division between the rocks with dominant pyroxene (i.e. those with 'dry' ferromagnesian minerals low in alumina) and those characterized by hornblende and biotite. About 57 % of the 415 rocks for which this ratio is given have values of 0–5 % or 95–100 % (i.e. in a clear majority of these rocks pyroxene is either exclusive of hornblende and biotite, or vice versa) and in less than 4 % of the total does the value lie between 45 % and 55 % (i.e. pyroxene about equal to hornblende and/or biotite). These values are about the same in subdivisions of the total according either to felspar or to colour-index; for rocks with andesine-labradorite (An_{50}) the proportion in which pyroxene is about equal to hornblende and/or biotite is still only 6 %. Biotite and hornblende are more commonly exclusive among soda-felspar rocks, pyroxene among lime-felspar rocks. (The boundary between Shand's metaluminous and subaluminous reaction types falls at or near 100 %). The nature of the dark minerals does, therefore, provide a basis for differentiating between two series of rocks, since in 96 % of the total number either pyroxene or hornblende + biotite is clearly dominant or exclusive. The two series, however, are not chemically distinct but parallel. The relatively sharp distinction between them suggests that something may be learned by studying their frequency-







Figs. 1 to 3.

DIORITES, GABBROS, and ANORTHOSITES

Fig. 1 COLOUR-INDEX (Dark minerals, volume %)

.... Ab > An } Plagioclase
– – – – An ≯ Ab }
———— Total

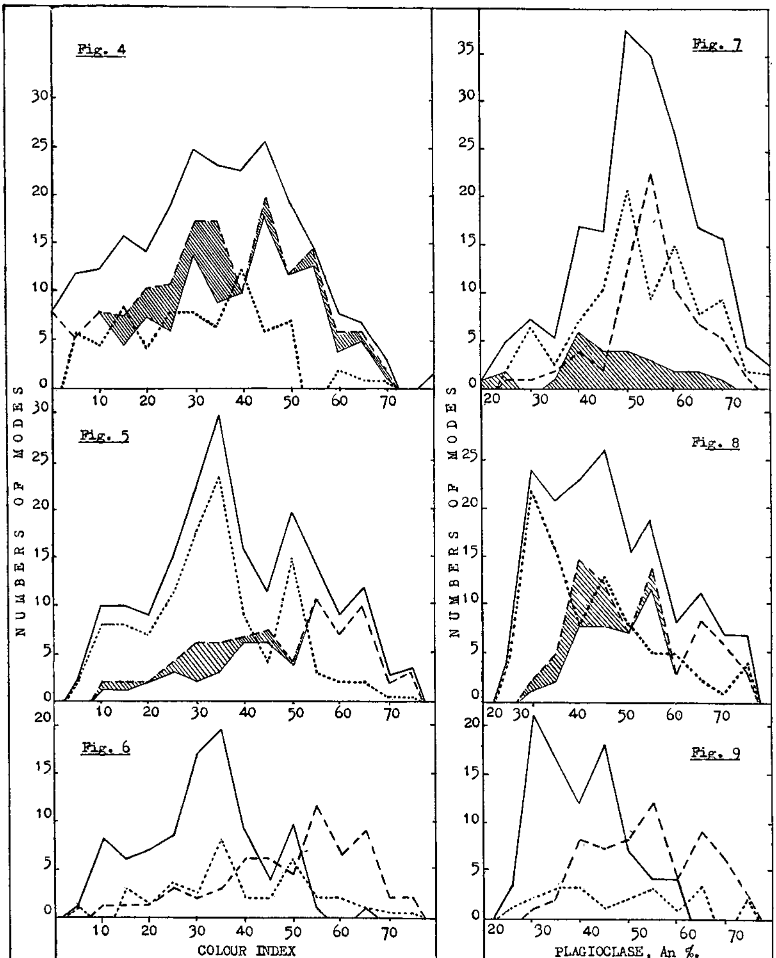
Fig. 2 COMPOSITION OF PLAGIOCLASE (An %)

.... Colour-index < 40
– – – – Colour-index ≯ 40
———— Total

Fig. 3 NATURE OF DARK MINERALS, expressed as

$$\frac{\text{Pyroxene + uralitic amphibole}}{\text{Pyroxene + amphibole + biotite}} \times 100$$

Ab > An } Total
An ≯ Ab }



Figs. 4 to 9. DIORITES, GABBROS and ANORTHOSITES.

	COLOUR-INDEX	PLAGIOCLASE, An %.
Pyroxene > Hornblende + Biotite	Fig. 4. .... Ab > An (75 modes) — — — An ≥ Ab (159 modes) ——— Total (234 modes) Shaded An ≥ Ab and Quartz > 2%.	Fig. 7. Colour-Index < 10 (27 modes) Shaded 10–40 (96 modes) .... > 40 (73 modes) — — — Total (192 modes) ———
Hornblende + Biotite > Pyroxene	Fig. 5. .... Ab > An (111 modes) — — — An ≥ Ab (73 modes) ——— Total (184 modes) Shaded An ≥ Ab and Biotite > 20% of dark minerals	Fig. 8. Colour-Index < 40 (85 modes) .... > 40 (71 modes) — — — Total . . . (156 modes) ——— Colour-index > 40 and Biotite > 20% of dark minerals Shaded
	Fig. 6. Biotite, % of dark minerals <20 Ab > An .... An ≥ Ab — — — >20 ———	Fig. 9. Biotite, % of dark minerals <20 Colour-Index < 40 .... > 40 — — — >20 . . . . ———

distribution separately. This is done in figs. 4, 5, and 6 for colour-index and in figs. 7, 8, and 9 for felspar.

The colour-index diagrams all show the division at 40 (or 45) and also that this division is due to the more typical rocks—i.e. to those with labradorite and bytownite in the pyroxene series (fig. 4, dashes) and to those with oligoclase and andesine in the hornblende and biotite series (fig. 5, dots). If the quartz-bearing pyroxene-labradorite (and bytownite) rocks are excluded (shaded portion, fig. 4) the division is nearer 35 than 40 and the mafelsic types are clearly dominant. Among the hornblende- and biotite-andesine (and oligoclase) rocks, although the division is at 45, 40 is also a very low value (fig. 5, dots). A low frequency at a colour-index of 40 is, therefore, common to the typical members of both series. The division does not appear among the pyroxene rocks with oligoclase or andesine or among the hornblende and biotite rocks with labradorite or bytownite, but the former group is mainly felsic (fig. 4, dots) and the latter mainly mafelsic (fig. 5, dashes), and they overlap at a colour-index of 30–50; rocks of the hornblende-biotite series with labradorite or bytownite mainly have essential biotite if the colour-index is below 40, but are almost all without it if it exceeds 40 (dotted line and shaded portion, fig. 5).

Fig. 6 shows the strong correlation between essential biotite, soda-felspar, and a felsic character on the one hand and between absence of essential biotite, lime-felspar, and mafelsic character on the other; further, that among the rocks without essential biotite those with oligoclase or andesine are more numerous below a colour-index of 40, and those with labradorite and bytownite at and above a colour-index of 40.

This type of frequency-distribution suggests the existence of two overlapping groups, each of which if it could be considered separately would show a fairly symmetrical frequency-distribution about a typical value (in this case a colour-index of about 30–35 and 50–55 respectively). The position of the low value between the two maxima depends on the relative abundance of the two groups. Where the felsic group is dominant, as in hornblende and biotite rocks with dominant soda-felspar (fig. 5, dots) or those with essential biotite (fig. 6, continuous line), it lies at 45; where the mafelsic group is more abundant, as in pyroxene-labradorite rocks *without* essential quartz (fig. 4), it lies at 35. (The rather more marked displacement of the division among rocks of the hornblende and biotite series may also be due partly to the fact that these dark minerals contain the equivalent of pyroxene plus some felspar or felspathoid.) When one group greatly outnumbers the other the former overlaps and conceals the latter (continuous line, fig. 1, in which the mafelsic rocks are swamped by the felsic). The colour-index value of 40 seems to mark a rough natural division, because it is the low value produced by the overlapping of the two groups when they are about equal in numbers (as in the case of the typical gabbros and the felsic gabbros *including* quartz-bearing varieties (fig. 1, dashes). It has the additional practical advantage that it is the point above which, in general, the dark minerals appear about equal in amount to the light ones.

Figs. 7, 8, and 9 show that the series with dominant pyroxene and with dominant hornblende or biotite overlap considerably as regards the composition of the felspar, most of the former lying between An_{40} and An_{70} and most of the latter between An_{30} and An_{60}. Many rocks of the pyroxene series have a value of An_{50} and the majority, whether felsic or mafelsic, lie above this value (fig. 7); An_{50} is actually the typical value for the felsic series and An_{55} for the mafelsic. Among rocks of the hornblende and biotite series the vast majority of those with essential biotite lie below An_{50} (fig. 9, and shaded portion of fig. 8), while most of those without essential biotite are mafelsic and have about 50 % or more of anorthite in the felspar, although many have less than this (fig. 9, dashes). Excepting for holofelsic rocks, which are almost confined to the pyroxene series, the point above which rocks in which the dominant dark mineral is pyroxene predominate over those in which it is hornblende or biotite lies between An_{50} and An_{45} (rather nearer the latter value than the former), and not at An_{50} as assumed by Rosenbusch when he substituted this limit between diorite and gabbro for one based on the dark minerals. The striking nature of the transition is brought out in fig. 10. At An_{45} there are twice as many rocks with dominant hornblende and/or biotite as with dominant pyroxene; at An_{50} there are only half as many.

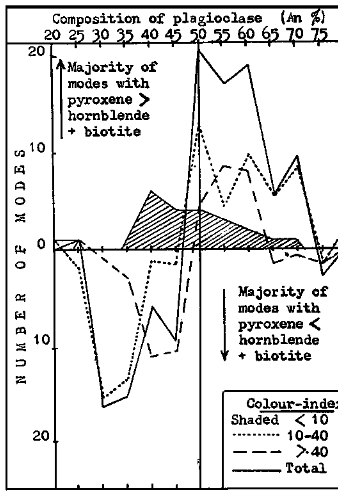


Fig. 10

Figs. 4–9 therefore constitute a case for utilizing a colour-index of about 40 and a plagioclase composition of An_{47-48} as the limits in table I.

These limits should not be too rigidly applied, especially as neither the colour-index nor the composition of the felspar can be very accurately determined. In applying such limits it would seem best to place rocks falling on or very near them with the adjacent types with which their affinity is greatest. For example, the more typical diorites (the mica-diorites of Rosenbusch) may be permitted to extend up to An_{50}. Rocks falling near the colour-index boundary of 40 should be grouped with the diorites if their felspar is more sodic and with the gabbros if it is more calcic; thus diorites will in practice range up to rather more than 40 and gabbros down to rather less than 40.

It is suggested that the term *meladiorite* should be used for mafelsic diorites or soda-gabbros; this only slightly extends the sense of the term as used by Johannsen and by Niggli, whose lower limit for it is a volumetric colour-index of 50, whereas the limit of 40–45 here proposed corresponds roughly to 50 % *by weight* of dark minerals. Similarly the felsic gabbros may be termed *leucogabbros*; this term is used by Niggli in practically the same sense. The prefix *leuco*, implying a colour-index lower than usual, is normally applied to holofelsic rocks, because most igneous rock-types are felsic, but it seems quite logical to use it to indicate the felsic variants of mafelsic types.

There appears to be no definite discontinuity between the holofelsic and felsic rocks (fig. 4, dotted line), but practically all the rocks in the data called anorthosite contain some dark minerals, ranging up to 10 % or rather more. As this is the conventional limit used in most classifications it will be adopted here as the boundary between holofelsic and felsic types. The distribution of the holofelsic rocks, so defined, with relation to the composition of the felspar (shaded portion of fig. 7) shows a discontinuity between the oligoclasites on the one hand and the andesine- and labradorite-rocks on the other, but no division near An_{50}. It appears from this diagram that andesine-rocks are more common than labradorite-rocks, but this is due to the overweighting of the data with Buddington's modes (1944) from the predominantly sodic Adirondack anorthosite, and to the fact that many published descriptions of anorthosites quote the felspar as labradorite without giving its composition, and cannot therefore be used in fig. 7. If these are taken into consideration, it appears that labradorite-rocks predominate over andesine-rocks among published anorthosite modes, which therefore seem to have a range and distribution similar to that of rocks of the pyroxene series in general. Accordingly it is proposed that the An_{47-48} boundary be used in the same manner as for other rocks, the term anorthosite being used alone to signify rocks composed predominantly of plagioclase ranging from andesine-labradorite to labradorite-bytownite, those composed of an andesine with well under 50 % of anorthite being called andesine-anorthosite or andesinite. The collective term *leucodiorite* (used by Johannsen in a narrower and by Niggli in a broader sense) may be used to cover oligoclasite and andesinite. Rocks falling near the colour-index limit of 10 should be placed with anorthosite rather than leucogabbro, since anorthosite is to be considered a major type on account of its quantitative importance.

As an upper limit to the mafelsic diorites and gabbros a colour-index of 70 is suggested because while there are many modes with an approximate colour-index of 65 there are very few indeed with one of 70 or more. Rocks with more than about 70 % of dark minerals should be called gabbro-pyroxenites, &c. Among the many modes of pyroxenites and hornblendites of different kinds listed by Tröger (1935), the vast majority have 100 % of dark minerals and are truly holomafic. We have, therefore, the colour-index ranges suggested but not adopted by Johannsen (1939), of 0–10–40–70–100.

A consideration of hypabyssal and volcanic rocks indicates that the same divisions can be used for them. For the purposes of this investigation, the grain-size range proposed for the gabbro-dolerite-basalt series by the British Association Committee on Petrographic Nomenclature (A. K. Wells, 1936) has been adopted. A collection of 115 modes of 'hypabyssal' rocks, so defined, has been made and they have been plotted in two series (those with dominant pyroxene and those with dominant hornblende or biotite respectively) in fig. 11 for colour-index and in fig. 12 for felspar. The rocks with dominant pyroxene, mainly dolerites (96 modes), far outnumber the others. They have a high concentration about a colour-index of 45; there are many below 40, but these are mostly 'granodolerites' containing much micropegmatite. Practically all dolerites have a plagioclase of composition between An_{48} and An_{67}. Data for microdiorites and diorite-porphyries are scarce, and it was found that most of the rocks so called in the British Museum collection were either microgranodiorites or granodiorite-porphyries, or devitrified andesites or dacites. Of the few of which the modes lie within the chosen limits, practically all have felspar with 40% or less of anorthite. They show no clear division as regards colour-index, but if their numbers are multiplied by five to make the total comparable with that of the dolerites, 40 is the value below which rocks with dominant hornblende or biotite and above which those with dominant pyroxene are predominant.

Adequate data for the volcanic rocks have been difficult to obtain because of the abundance of merocrystalline types in the dacite-andesite series, and of the relative scarcity of silica-saturated basalts. As it is, no attempt has been made to exclude rocks which have, or may have, more than 10 % of normative quartz occult in a glassy matrix, the only rocks excluded as dacites being those so defined by Rosenbusch (1907, p. 993) by the presence of first-generation quartz. There is accordingly a greater proportion of rocks of low colour-index in the data for volcanic than for plutonic and hypabyssal rocks, despite the absence of volcanic equivalents of the anorthosites. Few modes could be found for basalts, because most basalts contain some olivine; and few authors have considered it worth while to attempt quantitative mineralogical analyses of andesites, which normally consist largely of very minute felspars in a glassy matrix. A few andesites were selected from the British Museum collection as suitable for micrometric analysis, and the proportions of phenocrysts and matrix, and of different constituents of the matrix, were estimated separately. A rough correction was applied to the results obtained for pyroxene and 'ore'-grains in the matrix, to compensate for the fact that these are normally less in diameter than the thickness of the section. In some cases it was necessary to estimate by eye the approximate composition of the matrix. The few fresh saturated basalts available were also measured.

Plotting the results (109 modes) together on the colour-index co-ordinate, the frequency-distribution shown in fig. 13 was revealed, giving once again a deep division at 40, with a peak at 10 due to the andesites and at 50 due to the basalts. The low typical value for andesites may be due not only to the presence of many rocks with occult quartz, but to the fact that the glassy matrix also contains occult dark minerals. To obtain a frequency-distribution more directly comparable with that of the intrusive rocks, an attempt was made to correct the colour-index of merocrystalline rocks for this. By a comparison between the modes and norms of rocks for which both were available, it was found that on the average the potential colour-index of the glass is about 20 % of the actual colour-index of the crystalline material considered separately. If the colour-index values are corrected in this way, the result is the frequency-distribution shown by the line of dots in fig. 13 with a typical value ranging from 10 to 20 and a minor peak at 30. This line of dots represents the hyalopilitic and pilotaxitic lavas, which roughly coincide with the andesites and which are distinguished texturally because most lavas with plagioclase have pyroxenes as their . 'nant

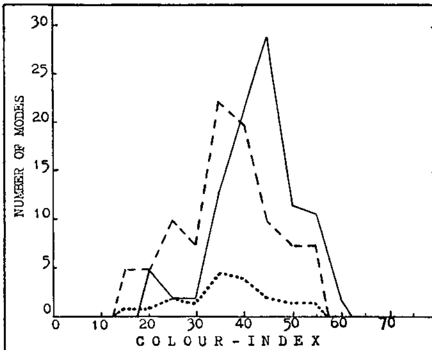


Fig. 11. DOLERITES and MICRODIORITES

——— Pyroxene > hornblende + biotite (97 modes, mainly dolerites).

.... Hornblende + biotite > pyroxene (19 modes, mainly microdiorites and lamprophyres).

– – – – The same (scale five times larger).

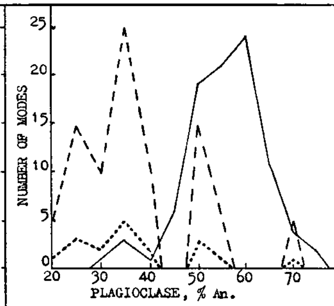


Fig. 12. DOLERITES and MICRODIORITES.

For key see Fig. 10.

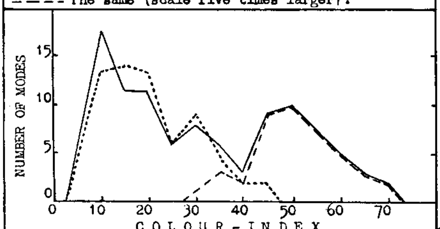


Fig. 13. ANDESITES and BASALTS

——— Total, percentage of actual dark minerals.

.... Hyalopilitic and pilotaxitic } corrected for occult dark minerals

– – – Intersertal and intergranular } corrected for occult dark minerals

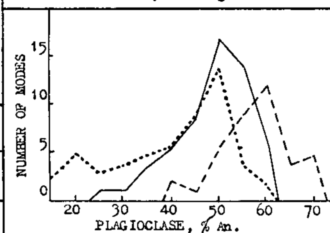


Fig. 14. ANDESITES (including cryptodacites)

.... Plagioclase of matrix.

– – – – Phenocrysts

——— Average plagioclase developed.

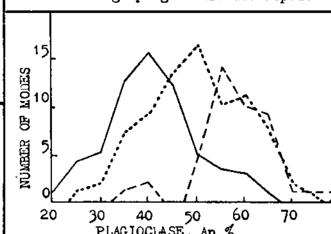


Fig. 15. ANDESITES and BASALTS

——— Estimated potential plagioclase in 63 hyalopilitic and pilotaxitic rocks.

.... Normative plagioclase in 335 rocks called basalt. Scale five times reduced. (After Bowen).

– – – Modal plagioclase in 46 intersertal and intergranular rocks ("basalts")

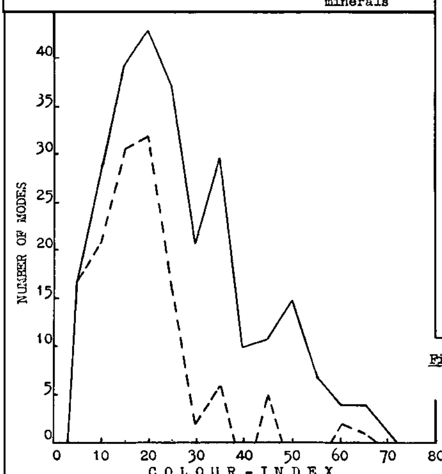


Fig. 16. THE GRANODIORITE-DIORITE SERIES.

——— 269 modes of hornblende and biotite-granodiorites, quartz-diorites and diorites (including mafelsic types).

– – – Granodiorites and quartz-diorites alone.

dark minerals; the other line (dashed) represents the intersertal and intergranular rocks, mainly basalts, which are almost unaffected by the correction. The result is still to show that there are few lavas with a colour-index of 40, and that below this andesitic types and above it basaltic types predominate. The few andesitic types with a higher colour-index than 40, and the basaltic types with a lower colour-index, are all characterized by labradorite.

It is difficult to compare the composition of the felspar in andesitic types with that in basalts, because of the great difficulty of estimating without analysis the average composition of the total (including occult) felspar of andesites, or even of the felspar actually developed. Fig. 14 (dashes) shows that the phenocrysts of andesites are generally of labradorite and are typically more calcic than the average (normative or modal) felspar of basalts (fig. 15, dashes). The matrix felspar is much more sodic but is nevertheless more calcic than the average felspar of diorites (fig. 8, dotted line). The felspar actually developed, obtained by averaging these two, virtually coincides with Bowen's curve (fig. 15, dotted line; Bowen, 1927, p. 140, fig. 40) showing the frequency-distribution of normative plagioclase in 335 rocks called basalt. An attempt was made to estimate the frequency-distribution of the average potential (including occult) plagioclase in 63 andesites. The residual glass was assumed to contain at least half of its volume of plagioclase of a composition somewhere between that of the matrix plagioclase and An_{10}, and maximum and minimum values between which the potential average plagioclase probably falls were found for each rock. The means of these respective maximum and minimum values were plotted as a frequency diagram, which is shown in fig. 15 in conjunction with that for the plagioclase actually developed in 46 rocks of basaltic type. The respective typical values are An_{40} for andesitic and An_{55} for basaltic types, the former being mainly below and the latter mainly above An_{50}, though they overlap at this point. The frequency-distribution of the potential plagioclase has the same range as that of the matrix plagioclase (fig. 14), but the maximum frequency of the latter is at a higher value, i.e. An_{50}. The symmetrical nature of the frequency diagram for the potential felspar of andesites suggests that the method of estimation used, while rough and ready, is accurate enough for practical purposes. If it indicates a predominance of albite over anorthite, the rock in question should be called andesite-basalt (e.g. alboranite, miharaite, mijakite). Some rocks of basaltic type (e.g. Markle basalt) have an abnormally low colour-index owing to enrichment in felspar phenocrysts, and should be called *leucobasalts*. The mafelsic lavas with oligoclase and andesine are all of basaltic type and should be called oligoclase-basalts (e.g. spilites) and andesine-basalts.

The same limits, with the same proviso as regards overlap of boundaries, can therefore be applied to the lavas as to the intrusive rocks, using texture instead of the nature of the dark minerals as one of the diagnostic characters.

Chemical data.

About a third of the modes collected from the literature were accompanied by chemical analyses, which are also available for a few of the rocks of which the modes have been micrometrically determined. These analyses have been plotted in various ways, using distinctive symbols to indicate the dominant dark minerals, the composition of the felspar, and the relative abundance of the dark and light minerals, in order to show how far the limits suggested for various types reflect chemical distinctions.

Since the field under discussion only covers rocks with plagioclase as the predominant felspar and at or slightly above the silica-saturation level, it is not to be expected that any definite segregation of types can be demonstrated about any given silica percentage. A study of silica percentages reveals that while Hatch's limiting value of 52 % is an approximate upper limit to mafelsic rocks (using the colour-index of 40 as the boundary between felsic and mafelsic), there are many rocks with a lower silica content which most petrographers would agree to call diorites (i.e. rocks with dominant andesine and subordinate hornblende and biotite), while many typical quartz-gabbros have a higher silica content. There is a rather more definite segregation of the lavas, nearly all basalts and andesite-basalts having less than about 54 % SiO_2 and nearly all andesites having more than this. As the relevant diagrams show such a marked overlap of types they have not been reproduced.

The relation of the modal limits proposed to chemical composition is best demonstrated by means of the Niggli values[1] *al-fm-c-alk*, which express the general mutual relationships of the bases. This can be fully shown on two triangular diagrams each of which is a projection of the *al-fm-c-alk* tetrahedron. Figs. 17, 18, and 19 (plate XXV) show all the analyses plotted on the $al+alk:fm:c$ triangle and figs. 20, 21, and 22 on the $c+fm:al:alk$ triangle. Both sets of triangles show that no single one of the characters which have been used to define diorites and gabbros

[1] $al:fm:c:alk = Al_2O_3 : 2Fe_2O_3+(Fe,Mg,Mn)O : (Ca,Ba,Sr)O : (K,Na)_2O$ (molecular values); $al+fm+c+alk = 100$.

actually separates chemical types; the least satisfactory character from this point of view is the nature of the dark minerals, and the most satisfactory the colour-index. If, however, all the characters are taken into account, it can be shown that the modally defined types here suggested correspond quite closely with definite fields in the Niggli triangles, allowing for a certain amount of marginal overlap. The few exceptions are nearly all mineralogically unusual rocks, or rocks lying on or near the modal limits suggested; if therefore they had been given symbols according to the principle of placing rocks on or near a modal boundary with the adjacent major type which they most resemble, the correspondence would be even closer.

Thus in fig. 17 (the $al+alk:fm:c$ triangle for diorites, gabbros, and anorthosites) it can be seen that for all the holofelsic rocks $al+alk > 4fm$; for oligoclasites and andesinites $al+alk > 2c$; for typical (labradorite-) anorthosites and bytownite-anorthosites $al+alk < 2c$; andesinites and typical anorthosites lie close together on either side of the line $al+alk = 2c$, reflecting the fact that they constitute a natural group with the plagioclase averaging about An_{50}. For most diorites, $al+alk < 4fm$, $> fm$; exceptions with $al+alk < fm$ all have $al+alk > 2c$ (i.e. they are types with fm high at the expense of c). Gabbros and meladiorites all have $al+alk < fm$, $< 2c$. For leucogabbros $al+alk < 2c$, $> 0{\cdot}25fm$, $< 4fm$. For hornblende- and biotite-diorites $al+alk > 2c$. Thus hornblende- and biotite-diorites are almost quantitatively marked off from gabbros and meladiorites; leucogabbros overlap gabbros and pyroxene-diorites, while pyroxene-diorites overlap leucogabbros and hornblende- and biotite-diorites.

In fig. 18 the dolerites correspond in position to the gabbros, and a number of dioritic lamprophyres fall with them. Hypabyssal equivalents of the typical diorites are relatively uncommon. Among the volcanic rocks (fig. 19), the andesites nearly all have $al+alk > 2c$, $> fm$, $< 4fm$; the basalts have $al+alk < 2c$ and $< fm$; for andesite-basalts $al+alk < 2c$, $> 0{\cdot}25fm$ and $< 4fm$.

In fig. 20 (the $c+fm:al:alk$ triangle for diorites, gabbros, and anorthosites) all the analyses show $al > alk$ (this demonstrates the absence of peralkaline rocks from the field under consideration). The holofelsic rocks all have $al > 40$. For gabbros, meladiorites, bytownite-anorthosites, and some leucogabbros, $c+fm > 7alk$. For diorites, anorthosites, andesinites, oligoclasites, and the rest of the leucogabbros, $c+fm < 7alk$, $> alk$. For leucogabbros and anorthosites (labradorite-rocks) $al > 2{\cdot}5alk$; for hornblende- and biotite-diorites, andesinites, and oligoclasites

$al < 2{\cdot}5alk$. As in fig. 17, the andesine- and labradorite-anorthosites lie close together.

In fig. 21 the compact distribution of the dolerites reflects their remarkable uniformity of composition. They are fairly definitely marked off from the microdiorites and dioritic lamprophyres by the line $c+fm = 7alk$. Among the volcanic rocks (fig. 22) it seems that a better separation of the basalts from the andesites is given by the line $c+fm = 6alk$ or $5alk$ than by the line $c+fm = 7alk$, but for nearly all the andesite-basalts, as for the leucogabbros, $al > 2{\cdot}5alk$, while for andesites $al < 2{\cdot}5alk$.

The principal points which emerge from these diagrams are, therefore, that meladiorites are not generally chemically distinguishable from gabbros; that typical diorites with oligoclase or andesine and subordinate hornblende or biotite are quite distinct both from gabbros and leucogabbros; that some pyroxene-diorites and some leucogabbros are intermediate chemically between typical diorites and typical gabbros; and that holofelsic rocks form a series distinct from the rest and clearly divisible into different felspathic types along the line from $al+alk$ to c, andesinites and anorthosites lying close together and evidently forming a single natural group. The modal limits suggested seem justified on the basis of the distribution of chemical data; even the two analyses of rocks with a colour-index exceeding 70 are distinguished from all the others in fig. 17 by having $fm > 4(al+alk)$, this division corresponding to that of the holofelsic rocks at the opposite side of the triangle.

Interpretation and suggestions for nomenclature.

The distribution of the modal data, while providing a basis for the delimitation of major types, also calls for explanation. It is suggested that the twofold grouping with relation to colour-index is the same as that pointed out by Daly (1933, p. 39) among calc-alkalic rocks in general: that of granite-granodiorite and andesite on the one hand, and gabbro, dolerite, and basalt on the other. The bulk of *typical diorites* are really the basic end of the granite-granodiorite series; their typical occurrence is as marginal facies or cupolas of granodiorite masses or as small stocks or bosses—i.e. as 'subjacent' rather than 'injected' masses (Daly, 1914, pp. 382–383; 1933, pp. 454–455). Average diorite is midway in chemical composition between average basalt and average granite (Daly, 1914, p. 382). Diorites, therefore, in general have a composition consistent with derivation from two parent materials, one of granitic and the other of basaltic composition, in approximately equal proportions; the result, perhaps, of the assimilation of sialic granite by simatic basalt magma followed by gravitational differentiation, as according to Daly (1914, 1933), or perhaps of the granitization of pre-existing basic rocks. The typical gabbros, dolerites, and basalts, on the other hand, seem to be truly the result of the solidification of a primary magma; the differences which they show from the oceanic olivine-basalts, which are presumed to be the typical simatic rocks, are such as can be explained by gravitational differentiation or by a comparatively slight contamination with sialic material such as one would expect to result from their characteristic mode of occurrence (dikes, sills, and laccoliths, i.e. floored intrusions presumed to have cooled relatively quickly). In the case of some norites, the contamination has been by aluminous sediment (Read, 1923, 1924) while hornblende-gabbros probably result from the ingestion of material rich in volatiles (Daly, 1933, p. 409). On this hypothesis of two radically different modes of origin, one would expect that while all sorts of gradations between typical diorite and typical gabbro should actually occur, they should be quantitatively less important than either type, as is in fact the case.

Since diorites are typically characterized by essential hornblende and biotite (the 'mica-diorites' of Rosenbusch) those with hornblende alone should always be called 'hornblende-diorite'. The *augite-diorites* are often associated with anorthosites, and tend to fall near them in the chemical diagrams. The 'gabbroic anorthosites', which are so called because they form marginal facies of anorthosite masses and which some authors (e.g. Harrison, 1944; Vogt, 1924) consider to represent their parent magma, are in many cases augite-diorites and may be called anorthosite-diorites. Augite-diorites pass with increasing anorthite content of the felspar into Spurr's 'belugites'. The type of this name quoted by Tröger (1935, p. 146) is simply a felsic gabbro with andesine-labradorite. The corresponding lava, *aleutite,* is not to be modally distinguished from pyroxene-andesites generally.

The meladiorites are chemically gabbroic, excepting when rich in alkali-felspar, biotite, or quartz. If chemically gabbroic, they should be given names which indicate their closer affinity with the gabbros than with the diorites. Thus the few rocks with dominant pyroxene in this division practically all have a basic andesine and are best called andesine-gabbros (or, if hypersthene is predominant, andesine-norites). The hornblende-meladiorites, which form the majority, are not distinctly marked off from the hornblende-gabbros; they form with them one series with felspar ranging mainly from An_{40} to An_{65} and with a typical value of An_{50-55}. There seems no reason why they should not be grouped under the general term *bojite*. This name was coined by Weinschenk (1898) to denote gabbros with dominant primary hornblende, and is so used by Johannsen (1937, p. 226); but Tröger (1934) discovered that the felspar of Weinschenk's type rock (from Pfaffenreuth, Bavaria) is medium andesine and therefore redefined bojite as 'dark hornblende-diorite'. It has been used recently in important papers by Pulfrey (1946) in the first sense and by Barth (1945) in the second, and has thus established itself in petrological literature with two mutually exclusive meanings. The obvious solution is to recognize that there is no essential difference between the gabbroic hornblende-meladiorites (i.e. those which do not contain essential quartz, biotite, or alkali-felspar) and the hornblende-gabbros, and to use the term bojite for both. If desired, those with andesine can be distinguished as andesine-bojites, this being nearly synonymous with hornblende-meladiorite. So used, bojite is synonymous with 'diorite' as originally defined by von Leonhard (1823, p. 104) and as used megascopically by the authors of the Quantitative Classification (1903, p. 183)—a sense which necessarily excludes typical diorite as currently used. The term bojite should not be used for meladiorites with abundant biotite or for those of appinitic type, since these are too alkali-rich to be chemically gabbroid.

The leucogabbros, though numerically important among the data, have not been treated as a major type because their concentration at a colour-index of 30–35 is probably due to the overlap of minor variations of the adjacent major types. Firstly, there are rocks resembling typical mica-diorites (but usually pyroxene-bearing), excepting that their felspar is labradorite. Such rocks, while included under the general heading 'leucogabbro', may be called labradorite-diorites. Secondly come the numerous quartz-gabbros and granophyric gabbros, which have been included in the data because they mostly contain less than 10 % of quartz. Both of these groups have a colour-index distribution like that of the typical diorites, with a maximum frequency of about 35. Thirdly come the basic marginal facies of anorthosite masses, ranging in colour-index up to about 30 but rarely above this; these may be called anorthosite-gabbros, anorthosite-norites, or anorthosite-bojites, according to the nature of their dark minerals. Lastly come those leucogabbros which are typical in the sense that they are felsic variants of normal gabbros; they include many norites (leuconorites) the felsic character of which reflects their origin as a result of the contamination of gabbroic magma by aluminous sediments.

The few dolerites with a colour-index of about 35 or less are all granophyric types with considerable micropegmatite and a felspar ranging down to andesine. Such types should be given the distinctive name *granodolerite* (Shand, 1917; Holmes, 1920). They have a range in colour-index close to that of the quartz-gabbros. Dolerites with a plagioclase more sodic than andesine-labradorite should be distinguished as andesine-dolerites or oligoclase-dolerites. The hypabyssal hornblende and biotite-rocks include a few lamprophyres (kersantite, spessartite, &c.) which are mafelsic types, but some of which overlap the colour-index boundary of 40. Here again the limits should not be applied too rigidly, especially to types like dolerites and lamprophyres, which are more clearly definable on a textural and qualitative than on a quantitative basis. Nevertheless, some rocks have been called kersantite or spessartite which, on account of their felsic character, should have been called 'microdiorite'. *Malchite* has been described variously and inconsistently as diorite-aplite and as a lamprophyre (Hatch and Wells, 1937, p. 251; Johannsen, 1937, vol. 2, p. 402), but Tröger's type specimen (1935, p. 147) occupies exactly the same position on the chemical diagrams as his typical diorite and andesite; it is, in fact, a typical microdiorite.

The nomenclature and delimitation of the volcanic types has already been discussed, excepting for one point: the separation of over-saturated types in which the quartz is occult in the residual glass. The majority of rocks generally described as andesites probably fall into this category. It is obvious from a comparison between fig. 13 and figs. 4 and 5, as well as between the chemical diagrams for plutonic and volcanic rocks, that most andesites, as defined by texture and by the minerals actually developed, are more felsic than most diorites. As their residual glass, as proved by analyses, commonly has the composition of a mixture of quartz and alkali-felspar, it may be said in general that the bulk of andesites correspond with granodiorites rather than diorites, a conclusion reached by Tyrrell (1921) from a consideration of chemical analyses. If, therefore, the term dacite is used in Rosenbusch's sense to mean andesites which are siliceous enough to be characterized by first-generation quartz, the dacite-andesite series as a whole can be considered to correspond to the granodiorite-diorite series, the boundary between dacite and andesite corresponding to a higher silica content than that between granodiorite and diorite. A close correlation can be demonstrated between the two series by combining the modal data for hornblende- and biotite-diorites, and meladiorites (fig. 5) with the data given for granodiorites and quartz-diorites by Johannsen (1937, vol. 2), Shand (1939), and Tröger (1935), and plotting the combined data as a colour-index frequency diagram (fig. 16). It will be seen that the frequency-distribution revealed by this diagram corresponds very closely with that shown for andesites and basalts in fig. 13. The maximum at 15–25 is rather higher than the corresponding value for andesites; this is to be expected, because hornblende and biotite correspond to pyroxene and iron ore plus some alkali constituents, which in typical andesites are present in the glassy matrix. The peak due to meladiorites corresponds to that of the basalts; it is relatively less important because the meladiorites constitute only a relatively small and aberrant part of the gabbroic rocks. The minor peak at a colour-index of 30, present in both diagrams, is probably due to overweighting with diorites and andesites of dioritic composition, since no granodiorites additional to those found in the literature mentioned are included, and dacites with first-generation quartz are excluded. This parallelism between the frequency-distribution of the plutonic and volcanic rocks tends to bear out the generally accepted genetic connexion as well as the chemical parallelism between the granodiorite-diorite series and the dacite-andesite series.

While admitting the difficulty of exactly delimiting the over-saturated andesite lavas with occult quartz, it should be possible to make a rough distinction by consideration of the refractive index and relative abundance of the glass. More data are required fully to work out the possibilities of this, but we know from the work of Tilley (1922, p. 27) that typical rhyolite-obsidian has about 25–30 % of normative quartz and a refractive index of less than 1·500, while the refractive index of trachyte-obsidian ranges from 1·505 upwards. If, therefore, the residual glass has a refractive index of less than 1·500 and amounts to more than one-third of the volume of the rock, the latter almost certainly contains more than 10 % of potential quartz. Such rocks should be called cryptodacites (= dacitoid, Lacroix, 1933, pp. 33, 192) to distinguish them from the true dacites with crystalline quartz. It is probable that most rocks of andesitic type with an abundant glassy matrix are really cryptodacites.

The majority of the coarse-grained rocks falling within the limits adopted in this paper contain little or no orthoclase. Those with essential orthoclase (the conventional lower limit of which is 13·3 % of the total felspar) should be distinguished as monzonitic diorites or gabbros (monzodiorite, monzogabbro). Most of them have pyroxene, generally with biotite, as the principal dark mineral; such monzonitic pyroxene-diorites have been given the name mangerite (Kolderup, 1903). The terms syenodiorite and syenogabbro are ambiguous because they are often used (e.g. by Hatch and Wells, 1937, pp. 196, 233) as synonymous with monzonite. Among the volcanic rocks, the andesites typically contain considerable occult orthoclase, which with the hypersthene and iron ore is equivalent to the quartz and biotite of the quartz-mica-diorites ('tonalites'); it is, therefore, unnecessary, and in practice impossible, to distinguish a group of orthoclase-bearing andesites, although holocrystalline types in which much orthoclase can be seen in the groundmass may be called trachytic andesites. Among the basalts, most of the orthoclase-bearing types also contain olivine and felspathoids, and are, therefore, outside the scope of this paper.

The boundaries suggested for the major types considered in this paper may seem indefinite and irregular to those accustomed to rigid and symmetrical pigeon-hole classifications, and who, perhaps, deny the existence of objective rock types. These critics should re-read the last chapter of Bowen's 'Evolution of the igneous rocks', in which he defends the traditional modal, loose classification. It is claimed that the present paper demonstrates within its limited field the existence of real objective types, which are in general those of the traditional classification; and that it roughly fixes rational quantitative limits to them which can be easily ascertained modally. The limits suggested have the advantage that, apart from distinction of meladiorite and leucogabbro from typical diorite or gabbro, they involve very little alteration to the names used for existing rocks. The system which comes nearest to the proposals made here is that of Niggli; indeed, if the colour-index limits of the Niggli system were weight instead of volume percentages they would be nearly equivalent to the volume percentages here used. The colour-index limits of 10–40–70 could, of course, be quite easily applied within the framework of the Shand or Johannsen systems.

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