The Petrology
of the
KHALE DOLERITE SHEET.

by

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Thesis presented for the Degree of Master of Science, to Rhodes University, Grahamstown.

- April, 1953. -

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ABSTRACT.

In the hills and in the plain of the Khale area are exposed two sheets of quartz-dolerite, the upper sheet being locally mushroom-shaped. The rock corresponds loosely to the Downes Mountain type of dolerite, and contains numerous horizons of coarse-grained dolerite-pegmatite.

The plagioclase felspars are described with special reference to the variation of grain-size, the features of zoned crystals, and the possible causes of a peculiar brown clouding in the basic zones of the crystals. Phenocrysts of augite and pigeonite, as well as plagioclase are recorded in the chilled contact rock.

The micrometric data indicate that the mineral composition of the various specimens is largely governed by the oxidation state of the iron, and that the Soret effect has caused the marginal rock to be enriched in basic elements.

Hydrothermal veinlets composed largely of chlorite occur in both the dolerite and the country rock, and evidence suggests that veins of both residual material and mobilised granite occur in the upper finer-grained dolerite.

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INTRODUCTION.

The purpose of the present investigation was to study some of the aspects of the mineralogy and petrology of the upper dolerite sheet exposed in the Khale Hills. While a certain amount of field evidence is presented, it is with a view to acquainting the reader with the general nature of the geological setting, rather than to supply detailed information regarding the structural aspects. To this end, the intrusion has been examined with great care in the field at significant points, while at others the author has confined himself to merely indicating the continuity of the outcrop.

The present work, it is hoped, will make a small contribution to the advancing knowledge of Karroo dolerites and similar rocks, and even in the absence of much new material, the data might be of some use in the confirmation of ideas expressed by previous workers. This necessarily brief paper will at least serve to point out some of the aspects in the petrology of the Khale Sheet, which are of interest.

The main bulk of the work has been carried out in the Department of Geology, Rhodes University. The period of field work was of necessity limited to a total of four weeks, while a certain amount of field work has been done in the Eastern Province examining comparable phenomena.

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ACKNOWLEDGMENTS.

It is difficult to express in brief terms the debt owing to Prof. E.D.Mountain, for his guidance and lively interest during the present investigation. In fields ranging from the loan of slides gathered for his own work, to a final critical reading of the manuscript, he has accumulated the sincere gratitude of the writer.

To Mr. E.J.Wayland, Director of Geological Survey, Bechuanaland, thanks are due for the initial suggestion that the Khale Sheet would be of interest, and for the loan of instruments and aerial photographs.

The writer was fortunate in having Dr. A. Poldervaart, now of Columbia University, introduce him to the area, and outline what specific studies might bear results.

Certain of his fellow-students deserve the thanks of the writer for their help on occasions, and in particular Messrs. D.K.Toorien, B.Sc., and O.Winfield, B.Sc., for carrying out an analysis of a pegmatite, and also Mr. J.B.Rogers, who accompanied him in the field for a fortnight.

For their kindness and hospitality, Mr. and Mrs. C.Beaumont, of the N.R.C.; Khale , are thanked.

The acknowledgments would not be complete without paying tribute to the paper: 'Karroo Dolerites of the Union of South Africa', by Prof. F.Walker and Dr. A. Poldervaart. Amongst other things, this work has supplied to the writer, and doubtless numbers like him, material which would otherwise not have been available.

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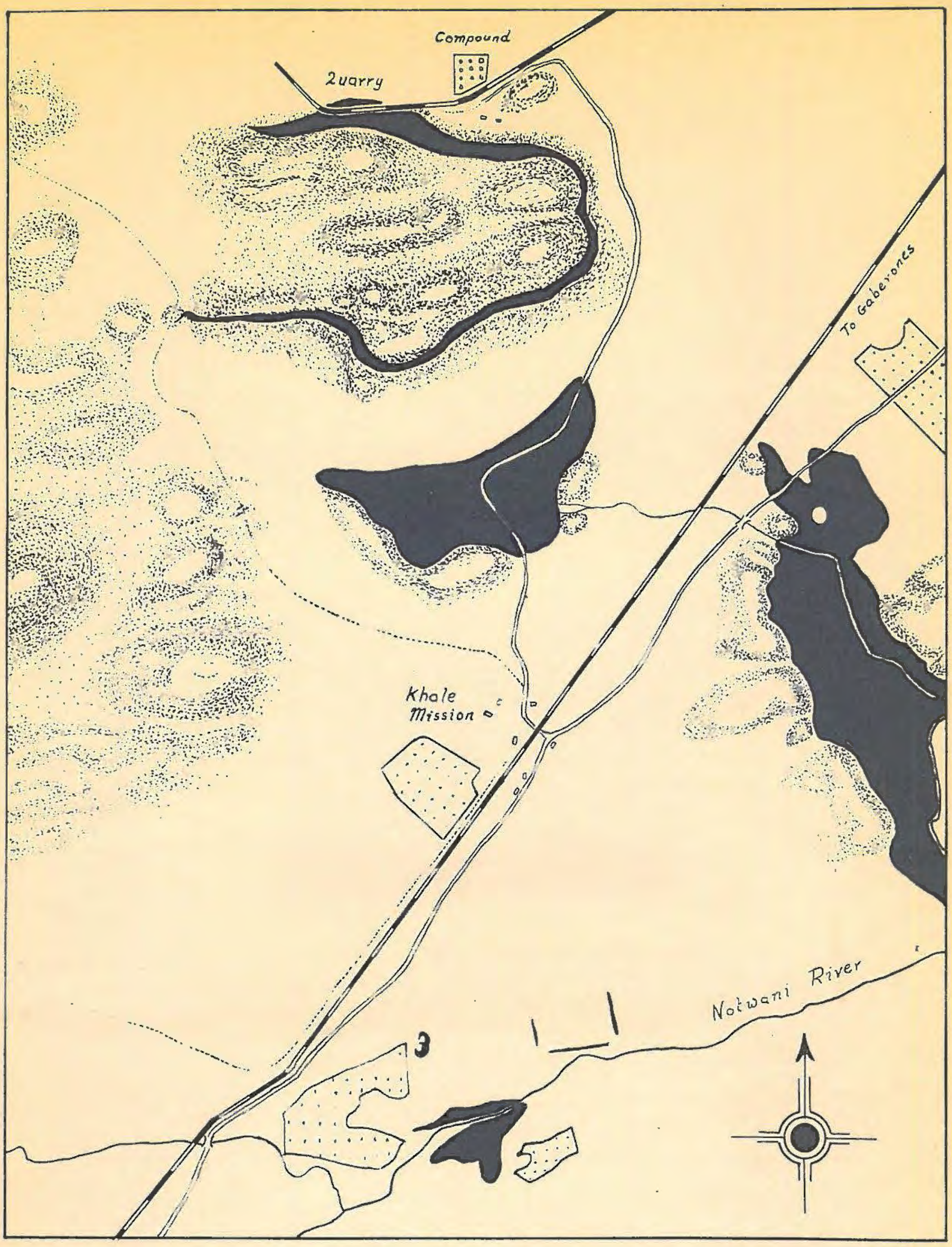
Plate I.

The North Hills of Khale.



A Sketch Map of

THE DOLERITES OF THE KHALE AREA

Scale approx. 1:30,000

Dolerites.

Cultivated lands.

Railways.

Roads

Footpaths.

Fig.1.

FIELD RELATIONSHIPS.

General Setting.

Some six miles to the south of Gaberones, in the Bechuanaland Protectorate, lies the small settlement of Khale, comprising a Mission Station, Native Recruiting Corporation Post, store and a few European houses. Khale lies on the main railway-line linking the Rhodesias to the Union, and also on the road serving the same purpose, the two running here parallel some few hundred yards apart.

The low hills around Khale provide pleasant relief from the monotonous, flat landscape so characteristic of this region. The hills are prominent topographic features rising a few hundred feet above the general level of undulating country, both being clad in mimosa, scrub and scanty grass. The two main hills, with their satellites, are granite outcrops lying to the west and north-west of the Mission Station, and are most conveniently designated the South and North Hills respectively. Except in the extreme west, where they are connected by low hummocks, the hills are separated by the general levle of the plain. Exposed in the middle heights of the North Hill and at various places on the plain, are limbs of an intrusion of acid dolerite, the study of which is the purpose of the present investigation.

Bare rock outcrops of granite and the dolerite are well exposed on the steeper hillsides, the lower slopes of which are strewn with rounded boulders, mostly of granite, some being of enormous sizes. The fortuitous perching of blocks has fashioned rude chambers and caves on the hillsides. The effective blanketing of the lower slopes by debris has obscured much of the outcrops, while the thick cover of sandy soil on the plain only occasionally favours the observer with continuous outcrops.

Forming the eastern boundary of the area investigated is the Notwani River, which is, for most of the year, no more than a string of muddy pools in the gravel-floored river bed. The river in places provides good exposures of rock.

It can be seen from aerial photographs of the area that there is a well-pronounced geological grain, which has found expression, to even the casual observer, in a parallel alignment of a number of features. The alignment of vegetation in rows is apparent from the air, even if not from the ground; the river itself follows this trend, although not rigidly, and the ridge and valley topography of the hills conforms also to this direction. As little interest attaches at this juncture to the nature of the country rock, scant attention has been paid to it.

The dolerites of Khale represent the surface exposures of two sheets which may locally deviate considerably from the horizontal. Vertically separated by an amount varying between 50 and 100 feet, the two sheets are not visibly joined, although they are undoubtedly offshoots from a common parent mass. As might be expected with a small body intrusive into a more or less massive country rock, a non-uniformity of thickness, dip and general structure is apparent; for this reason, designation as a sheet is to be preferred to the use of the term sill.

Upper Sheet.

The upper sheet is exposed around three sides of the North Hill, and is locally mushroom-shaped in the north, the upper contact showing both on a large scale and in detail marked transgression from a flat surface. Thus, on the hillside facing north, the upper contact may be seen to climb from close to the plain floor in the west, to within a short distance from the top of the hill and fall away again with equal rapidity towards the east. The impression of the domed nature of this part of the intrusion is further strengthened by the way in which the granite west of the quarry spreads over the rapidly diminishing dolerite outcrop in the manner of an eyelid covering the eye. It is on this facet of the North Hill that a large ballast quarry has been blasted out.

Just east of the compound housing the quarry labourers, the presence of a low granite hill brings home to the observer how rapidly the intrusion may change its attitude, or taper out altogether, for although only some 250 yards from the base of the main hill, and reaching in height well above the halfway level between floor and roof, the smaller hill exposes no dolerite at all. It must thus be assumed that north of the present outcrop in the quarry area, the intrusion either died out rapidly, or took a sharp turn to higher levels. The latter is the interpretation adopted by the author. A rough parallelism of upper and lower contacts is maintained around the two remaining sides of the hill where the dolerite is exposed, except that the intrusion as a whole thins out to the west. In no place, perhaps, does the intrusion exceed 150 feet in thickness, and the lower contact is always well above the level of the plain.

As previously mentioned, much of the hillside is effectively blanketed by rubble, and in all but one section facing the mission station, it is impossible to locate with any accuracy the lower contact. Locally the whole vertical section may be obscured by rubble with partly buried boulders of such great size that a false impression is given of their being in situ.

The upper contact shows also in detail considerable deviation from a plane surface, frequently being stepped, or interleaved for short distances with the granite. In all cases the contact is knife-sharp and the marginal dolerite is a chilled variety. Small sheets ranging in thickness from parts of an inch to several feet are common above the upper contact.

Lower Sheet.

Although not exposed as a continuous sheet, it is assumed that the various outcrops of dolerite in the plain are merely the exposed portions of a single limb. These could be classified as surface outcrops beneath low hummocks of granite, for, wherever the dolerite is exposed at the surface, it bears on its back a low dome, not usually more than thirty feet in height. This is presumably a natural consequence of its indurating effect on the granite. Whereas the upper contacts may be plotted and studied in precise detail, the lower contacts are everywhere obscured by overburden. It can be seen from the sketchmap that dolerite crops out in the plain in three main areas between the hills and the river, two lying south-east of the North Hill and the third further south, in the neighbourhood of a small orange orchard. All are associated with low granite hummocks around their periphery of outcrop.

At the N.R.C. offices, a well was sunk for the purpose of raising water, and although no records or recollections regarding its construction remain, it can be seen that dolerite was encountered, and appears to be some thirty feet below the surface. This can be taken to indicate that much of Khale is underlain at a relatively shallow depth by dolerite, which now outcrops at the surface where local upward swellings of the body took place during emplacement.

Summary.

Briefly, the main field relationships of the dolerite may be set forth:

(i) The upper sheet thins away to nothing towards the western face of the North Hill. The north face of the same hill indicates local swellings of the intrusion, giving it a mushroom shape there. The outcrop, as seen on the eastern and southern hillslopes, shows that, apart from this, the upper sheet is more or less uniform in attitude.

(ii) Much of the area appears to be underlain by a lower sheet, and where local upwellings of the magma occurred, the dolerite is now exposed in the plain beneath low granite hummocks.

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Explanation of Plate II.

Fig.1.

A small sheet of dolerite, about two feet thick, in granite.

Fig.2.

Xenolith of granite in the chilled dolerite of the upper contact zone. Note the rude columnar jointing of the xenolith, which contrasts with the ill-jointed nature of the enclosing dolerite.

Plate II.

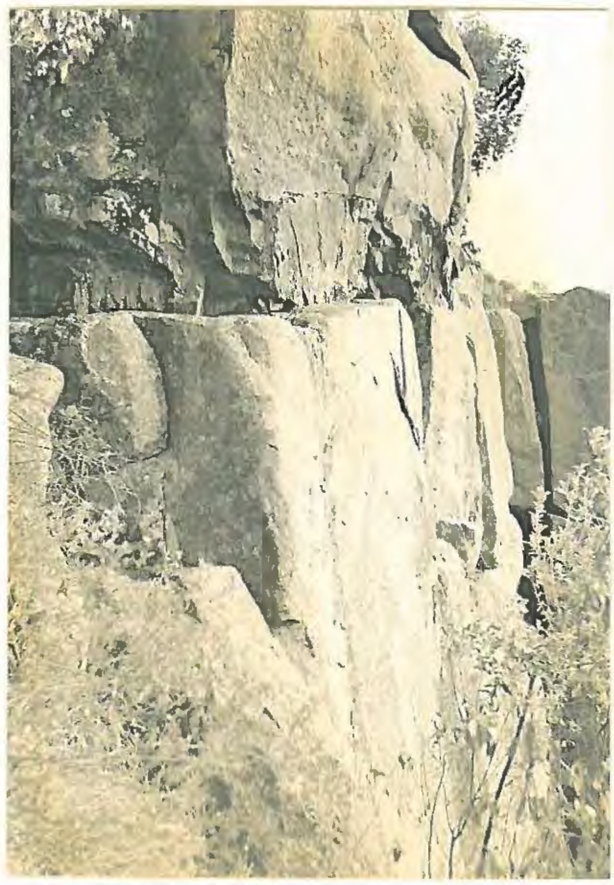

Fig. 1

Fig. 2.

Explanation of Plate III.

Fig.1.

Well-developed slickensided joint in the upper part of the western quarry face. The scale is indicated by the remains of a tree, about eight feet high, blasted by dynamite.

Fig.2.

Quarrying operations in progress. Notice the well-defined horizontal jointing of the medium-grained dolerite.

Plate III.

Fig. 1.

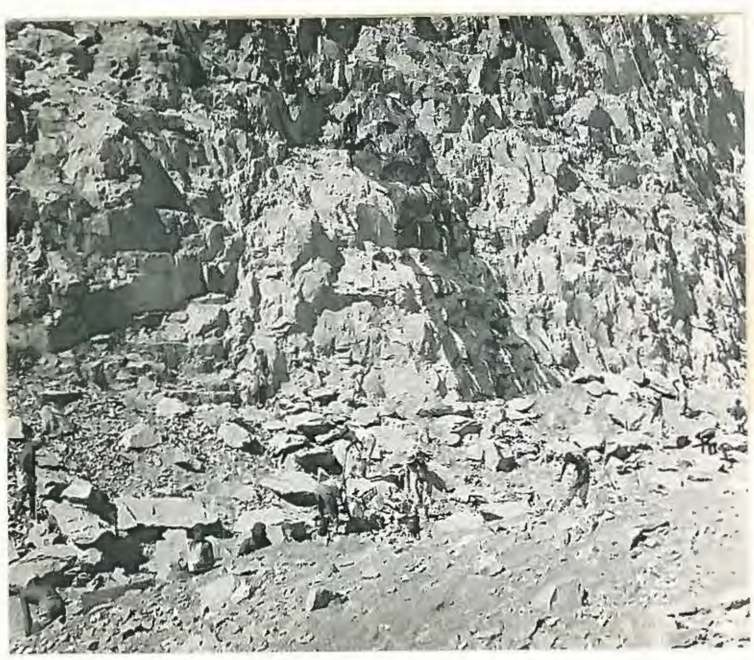

Fig. 2.

Jointing.

The joints of the area may be classed as:

(i) Contraction joints in dolerite.

(ii) Regional jointing of granite.

(iii) Columnar jointing of granite induced by the dolerite.

Measurements of the dip and strike of joints were carried out using the Brunton Compass. No great reliance could be placed on the compass readings, if precautions were not observed, as the dolerite shows strong magnetism. The influence may be strong enough to deflect the compass needle through 180°, but if the instrument be held more than five feet from the solid rock, the readings are consistent and fairly reliable. Where the outcrop is covered by broken debris, as on the quarry floor, the magnetic disturbance is least.

Joints in Dolerite.

Columnar jointing is feebly developed against the granite, a close-spaced horizontal jointing parallel to the contact being here more conspicuous.

A detailed study was made of the joints in the quarry, and wherever possible the attitude of joints in all other outcrops were measured. Just short of eighty near-vertical joints were measured, and these have been plotted on a frequency diagram. (See Fig. 2) From this it is seen that although there is considerable spread in the strike of these joints, there tend to be two dominant sets, striking at N30°W and N50°E.

Horizontal joints are well developed, as is well shown by the Fig.2 of Plate III. Those measured lie within a few degrees of the horizontal, with slight dips towards the north.

Contour Diagram of the Dolerite Joints.

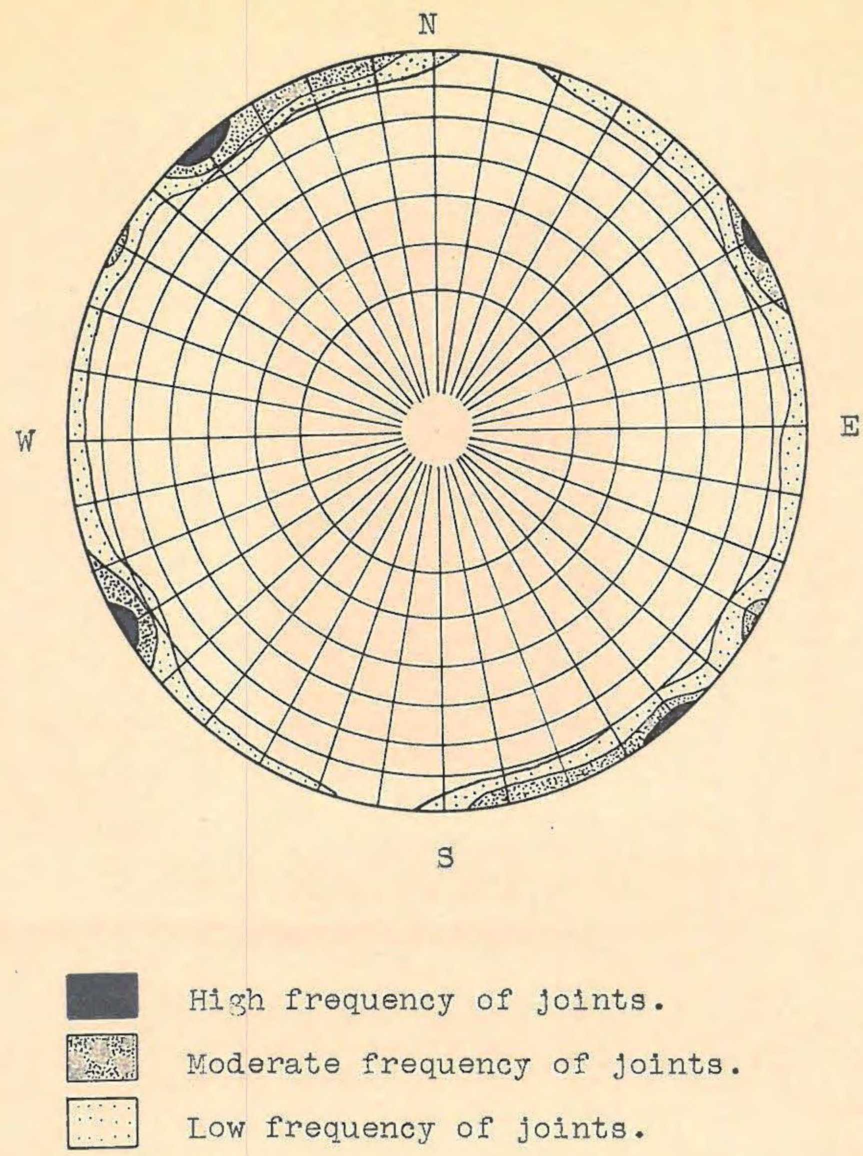

Fig. 2

Contoured diagram to illustrate the major dip and strike directions of the steeply dipping joints in the dolerite. Normals to the joint surfaces have been plotted on an equal area projection. Plotting is on the upper hemisphere.

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The facts of significance, regarding the origin of the joints, are considered to be:

(i) Deuteric mineralisation has introduced a wide, if common, assemblage of minerals along the vertical joints, as far up as the upper contact. This mineralisation may take the form of merely a thin film of chlorite along the fractures, or, with advancing grade, veins of epidote, actinolite and calcite up to three inches thick. Comparable mineralisation was not observed along the horizontal joint planes. The rude columnar jointing of the chilled variety appears to have encouraged the development of thin vertical veins of pegmatitic dolerite , even in the chilled rock.

(ii) Slickensiding along the vertical fracture planes shows differential movements to have occurred, and although the magnitude of movement is not known, it is certainly small. Poldervaart (1952) considers it to be measurable in terms of millimetres. Where slickensiding is best developed, the vein minerals become markedly fibrous or asbestiform. Prominent slickensiding does not appear to be a feature of the horizontal joints.

(iii) The joints are not strictly plane surfaces, but tend to be arcs of wide radius. This is most apparent in the better-exposed joints of the quarry.

(iv) The quarry face reveals that over short distances measurable in feet, the joints may multiply in number to form fracture zones with extensive mineralisation and slickensiding.

On the evidence of the mineralisation following the joint planes, it is clear that the near-vertical joints were initiated before the body had become com-

completely cool, and owe their origin chiefly to the stresses set up during contraction. Noting that where slickensiding is best developed, the minerals that are normally of prismatic habit may become fibrous or asbestiform, we may infer that the mineralisation and the stresses initiating the slight relative movements were essentially contemporaneous. Although the directions of strike of the steeply dipping joints show a wide spread, there are definite frequency maxima. This need not be taken as proof of the action of regional stresses, as the frequency maxima do not correspond with those measured for the granite.

The curved nature of the horizontal joints, and the absence of comparable mineralisation and slickensiding suggests that they are sheeting joints, due to a subsequent relief of load. As these horizontal joints tend to be closer-spaced near the upper contact, while still under a thick granite cover, it must nevertheless be accepted that contraction stresses have also played their part.

Regional Jointing of Granite.

The prominent joints of the granite were not examined with the same care as those of the dolerite, but a sufficient number of measurements was made to show that the major joint directions of the two do not correspond. As before there is considerable spread in the strike of the most prominent joints, and as such there might be local correspondence in the joint directions of the two rock masses, but the most frequently encountered strike directions of the acid rock were N10°W, with N80°E, the direction of the regional ~~jointing~~ grain, strangely subordinate. The strikes referred to are those of near-vertical joints, but in addition, there is sometimes developed a less prominent plane dipping at about 20° to the east, with the same strike as those first mentioned.

Columnar Jointing of Granite.

For a short distance above the upper contact, there is developed a rude form of columnar jointing in the granite. This, without doubt, is the result of induration by the younger intrusion, as the structure is confined to the immediate contact horizon, and rises and falls with the upper surface of the dolerite. A similar form of columnar jointing has been induced in small granite xenoliths in the dolerite, as shown in Fig.2 of Plate II.

PETROGRAPHY.

PETROGRAPHY.

The petrography of the Khale intrusion is most conveniently dealt with by describing separately the typical, medium-grained dolerite, the chilled contact phase, and the dolerite pegmatites.

Medium-grained Rock.

The Khale dolerite, a member of the tholeiitic magma type, corresponds loosely to the Downes Mountain type of dolerite, as defined by Walker and Poldervaart (1949). This is:

> "A medium- to coarse-grained, subophitic pigeonite dolerite.
>
> Columnar, magnesian pigeonite occurs in addition to augite. The two pyroxenes often form ragged, subophitic prisms with marked elongation and curvature. Both olivine and orthopyroxene are absent. Plagioclase forms zonal laths 0.6-1.2 mm. long.
>
> Chief characteristics are the subophitic texture, absence of both olivine and orthopyroxene, abundance of micropegmatite, and its association with the Hangnest type."

The micrometric analyses show that, in the main bulk of the rock, the weight percentages of the various minerals do not vary greatly; in the pegmatitic specimens and those within about twelve feet of the upper contact, however, the weight percentages of all the minerals vary considerably, even in successive specimens taken at intervals of a few inches. In Table 1 is given the mode of a specimen which is representative of the main bulk of the intrusion, and the modes of similar rocks described in the literature.

It will be noticed that the average mineral percentages for the typical rock of the Khale intrusion fall between those in the first and third columns in all cases, except with regard to the amphiboles and iron ore. It is a feature of this intrusion that the iron ore may comprise up to 20% and not less than 8% of the rock by weight in specimens which are not pegmatitic, while the percentage of the amphiboles, by weight, rarely drops as low as 3%. In like manner the percentage of the micropegmatite varies in different specimens, the highest being recorded as 14.7%. In no thin slice examined does the amount drop below 7.2%

This association of high amounts of ore, micropegmatite and amphibole is thus a characteristic of the body, and in a more detailed examination of the micrometric data, the underlying cause is seen to be an antipathetic relation between the ore plus acid mesostasis on the one hand, and ferromagnesian minerals on the other.

Table 1.

	1.	2.	3.
Olivine	-	-	-
Plagioclase	43.8	40.0	35
Pyroxene	42.1	34.2	28
Iron Ore	4.3	8.8	8
Biotite and Amphibole	.8	5.5	4
Micropeg. and Qts. Mesostasis	9.0	11.5	25

1. Downes Mountain type.
2. Khale type.
3. Dolerite Pegmatite type.

The normal, medium-grained rock is a typically subophitic quartz-dolerite, in which there is every indication of the earlier initiation of crystallisation of the felspars, as evidenced by the indentation of the pyroxenes by that mineral, or even the occasional complete poikilitic enclosure of small felspar laths by pyroxene. The grain-size is subject to variation with both distance from the contacts and location along a particular horizon at constant distance from the contacts. Within the small area of a single thin section, there may be small patches, a few millimetres in diameter, which are smaller in grain-size, and contain plagioclase of a more basic character. The irregular increase of grain-size of the felspars with increasing distance from the contacts has been studied in some detail, and the results are presented in the discussion of the mineralogy of that mineral. While two clino-pyroxenes, pigeonite and augite, are present, the latter is more abundant: pigeonite usually forms cores to the augite, discrete crystals and grains of large area being rather rare. All the textural evidence is in favour of the earlier initiation of crystallisation of the pigeonite.

In specimens containing the average amount of micropegmatite, the habit of the intergrowth is invariably interstitial, with the result that it is usually bounded by nearly straight edges, defined by the margins of the earlier minerals. As noted by numerous writers, the felspathic component of the micropegmatite and the outer zones of the plagioclase crystals apparently grade with optical continuity. Where the amount of micro-pegmatite is abnormally high, replacement textures become evident. In the penultimate stages, the plagioclase may survive only as a few scattered residual pathces within the intergrowth, the only proof of their former continuity being an ability to interpolate twin planes.

Most of the amphibole is secondary after the pyroxene, except in the interstitial mesostasis, characteristic of the more rapidly cooled rock. Here the amphibole, of striking blue-green colour, appears to be of primary crystallisation. The iron ore, so abundantly present, may show a variety of habits, from large skeletal crystals, to xenomorphic grains moulded on pyroxene. A more detailed description of individual mineral habits follows in the mineralogy.

The specific gravity of the rock, based on twelve determinations by accurate hydrostatic weighing, varies between 3.007 and 3.041, the main bulk of the intrusion yielding a value of 3.029.

Fine-grained Contact Rock.

Although no true glass has been produced, the rock is, for a few inches from the contact, an aphanitic type containing a small proportion of phenocrysts. The specific gravity of this rock is slightly higher than that of the medium-grained rock, yielding a mean value of 3.059.

Micrometric measurements show the average type to have the following volumetric composition:

Table 2.

Aphanitic Groundmass	93.7
Plagioclase	3.4
Pyroxene	2.9
Ore	-
F/P ratio	1.16

The groundmass has in thin section a mottled appearance, caused by innumerable dark patches enveloped in a reticulate pattern of leucocratic material. The texture probably results from the rapid crystallisation about separate nuclei of a greater proportion of the darker material, followed by the interstitial crystallisation of a slightly less mafic residuum.

It is interesting to note that the phenocrysts are essentially similar in composition to those of the medium-grained dolerite, the felspars being little different in anorthite content, while both pigeonite and augite are present. Slender plagioclase laths may reach lengths of 1 mm., but the pyroxenes are generally smaller, most commonly as equidimensional grains bewteen 0.1 and 0.5 mm. These phenocrysts tend to be grouped together as glomeroporphyritic aggregates. The contact basalt thus affords interesting evidence of the early crystallisation of pigeonite under near-intratelluric conditions.

Coarse-grained Rock.

The sheet is characterised by the abundance of coarse-grained schlieren, mostly in the upper half, that is, the upper 70 feet in the thicker parts. The coarse pegmatite may be examined in the upper quarry face, but is relatively rare in the lower parts of the face. The major rôle assumed by the pegmatites is made plain by the difficulty encountered in collecting suitable specimens of the normal rock in parts of the upper horizons of the sheet: the rounded surfaces of the rock necessitate the utilisation of angular blocks shaped by joints, for sampling, and here the impression is gained that the vertical attitude of thin pegmatite veins is related to the formation of the fractures.

Most commonly the pegmatites form horizontal or slightly inclined bodies which swell and shrink along their length, eventually tapering away to nothing. One small body could be traced from some point along its length, where it emerged from under surface rubble, for a distance of some fifty feet, although only a few inches thick. Where it tapered out eventually, it was no more than a streak as thick as a pencil line, but nevertheless clearly visible on the weathered surface. The more or less horizontal schlieren vary in thickness from parts of an inch to over six feet, and are characterised in the field by coarseness of grain, although not markedly different in colour from the medium-grained dolerite. On smooth, weathered surfaces of outcrops, they do appear darker, and their surfaces are somewhat pitted and raised above the surface of the other. The contact between the two is not sharp in handspecimens as an intermediate zone about a half-inch wide is usually present. In the case where the long pyroxene blades lie parallel to the contact, there is gained an impression of rapid change.

The micrometric data indicate that in all cases the ferromagnesian minerals are present in similar, or even greater proportions than in the medium-grained rock, and that the iron ore and acid mesostasis may be present in either greater or lesser amount. The feature will be discussed further in a more comprehensive survey of the data. Two modes are given below, in Table 3, and for comparison, the mode of the defined Dolerite Pegmatite type (Walker and Poldervaart, 1949).

Contrasted with the medium-grained dolerite, where the textures follow as a result of the early crystallisation of a large proportion of the plagioclase, the textures of the dolerite pegmatite are suggestive of a contemporaneous separation of the pyroxenes and the

Table 3.

Modes of Dolerite Pegmatites.

	1.	2.	3.
Plagioclase	35	36	32
Pyroxene	28	44	34
Iron Ore	8	6	16
Biotite and Amphibole	4	6	5
Micropegmatite and Qtz. Mesostasis	25	8	13

1. Dolerite Pegmatite type.
2. Pegmatite from Shale.
3. Pegmatite from Shale.

Note

The modes 2 and 3 above, are of dolerite pegmatites in which replacement processes do not appear to have been active.

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plagioclase felspars. Although graphic intergrowths between these two minerals are developed, the columnar habit is generally adopted by the pyroxene. Indentation of the plagioclase, and even complete poikilitic enclosure of large grains of pyroxene by the former are textures, which by themselves, would distinguish immediately the coarser-grained rock from the non-pegmatitic variety.

The non-uniformity of the rock is shown by a demarcation of the thin slices into areas, several millimetres in diameter, consisting of pyroxene, plagioclase, and ore, and in the extreme case on the other hand, areas without any of these minerals, composed of quartz, amphiboles, biotite, and alkali felspars. To both areas, micropegmatite is common.(Tomkeieff,in 1929, extended the use of the term 'taxitic' to describe this form of non-uniformity in specimens of dolerite pegmatite.) This non-uniform texture is not sufficiently coarse to allow the two varieties to be mechanically separated. Many of the specimens do not show such an obvious separation into small areas of different mineral composition, and are more uniform in appearance.

In the outer margins of the quartz-rich fractions the elimination of plagioclase, pyroxene and ore provides a fine illustration of several replacement textures. Individual pyroxene columns may be seen to be progressively altered to amphiboles of rich green and brown colours, by passing first through a zone of serpentinous character with low birefringence. In the outer periphery of these same segregations, the ore has been subjected to vigorous attack and converted partially or wholly to nests of equidimensional grains of brown biotite. Once again, the process is visually unfolded by tracing the sequence from skeletal and granular ore moulded on pyroxene, through a stage where the crystals are coated with a film of orange and yellow silicates. Just preceding the final elimination of the ore, it is found as buckshot-like granules embedded in the biotite nests. The segregations contain no plagioclase felspar, as evidenced by the absence of felspar with polysynthetic twinning. This absence of soda-lime felspar from the segregations is problematical. Whereas the low modal value sometimes encountered in the pyroxene-plagioclase-ore-micropegmatite patches is due in part to the replacement by micropegmatite, it is questionable whether the same process would operate to the complete elimination of plagioclase. An interesting structure has been developed by the replacement of alkali-felspar by green and olive-green amphiboles. It appears that the alkali-felspar was unstable in its environment, for a continuous grade may be followed from micropegmatite to a quartz-amphibole intergrowth, the intermediate stage between the two extremes being the intergrowth of quartz and highly altered alkali-felspar with a muddy appearance. Whereas the quartz component of the quartz-amphibole intergrowth is optically continuous, the separate areas of amphibole are not. The orientation of the section determines whether it resembles flamboyant or geometric types.

In the centre of these segregated patches, quartz is the chief mineral, enclosing ragged laths of zonal green biotite with brown cores, spherulites of chlorite, and acicular actinolite. The biotites show pleochroic haloes framing tiny zircons. Some of the rock-specimens as a whole are laced by veinlets of pale green chlorite which cut through all the minerals but quartz.

Another interesting structure is the curvature of the pyroxene blades. The highest angle of curvature recorded was 74°, in a crystal with the (100) twin plane near the vertical. This grain shows no signs of fracture, and the extinction position moves with the curvature. The enclosing felspars show no signs of fracture or anomalous extinction. In the handspecimen the curvature of the parting plane is like that of a thin flexible sheet which has been subjected to torsional stresses.

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MINERALOGY.

THE PLAGIOCLASE FELSPARS.

The plagioclase felspars show a number of interesting features, and of these, the variations in grain-size, the zoning, and the development of a brown clouding have been studied.

Grain-size.

Measurements of grain-size were carried out on a series of oriented specimens taken at measured intervals from the upper contact. These specimens were sectioned, the slices being cut in the horizontal plane, parallel to the contact.

The actual measurement of grain-size was attempted according to two methods. The first was that using a Dollar Integrating Stage in conjunction with a counting devise. By this method, intercepts across a large number of crystals in the slide were recorded, the sum being divided by the number of grains so measured. While the results were fairly consistent with the fine-grained specimens, it was found that the method is not suited to those of coarser grain. A more satisfactory method was devised by using a camera lucida attachment in conjunction with a planimeter. The microscope was placed on a drawing-board covered with a good quality cartridge paper, and the planimeter set on this in such a position that the pointer could cover the whole field of view quite comfortably. A torch bulb was attached vertically above the pointer, and connected to a dry cell, and a deep green filter used with the camera lucida. Using this apparatus, the outline of individual grains could be traced out, the filament of the bulb supplying a pin-point source of light in the field, and the area of each grain determined by reference to the standard magnification of the apparatus.

Between 40 and 50 felspar crystals were measured in each slide, and in deference to the statement by Lane, quoted by Alling (1936, p.323), that as thin sections are chance sections, the large grains in a thin section are the most significant in grain-size studies, those of small area were ignored. Naturally, phenocrysts were excluded, and each crystal first examined between crossed nicols to demarcate possible intergrowths. The average grain-area for each slide was then recalculated to the diameter of a circle having the same area, and the latter figure used as representative of the relative sizes of crystals.

The results obtained by this method were found to be much more consistent than by the other, although again, with average recalculated diameters greater than 0.5 mm., the measurements were not exact, due to the smaller number of suitable crystals in each slide, and distortion towards the edge of the field in the case of elongated crystals.

The Grain-Size Curve.

The curve (Fig.3 and Fig.4) shows very clearly the rapid increase in grain-size across the first 10 feet from the contact, followed by a slower increase, and the cessation of further regular increment. As seen from the two traverses from which the plots were taken, the grain-size is not initially constant along the strike at equal distances from the upper contact, but the two series of plots converge at about 12 feet.

The size increment is not continuous, but follows a series of steps. As can be shown in one case at least, this may be correlated with small variations in the anorthite content of the felspars concerned. It is

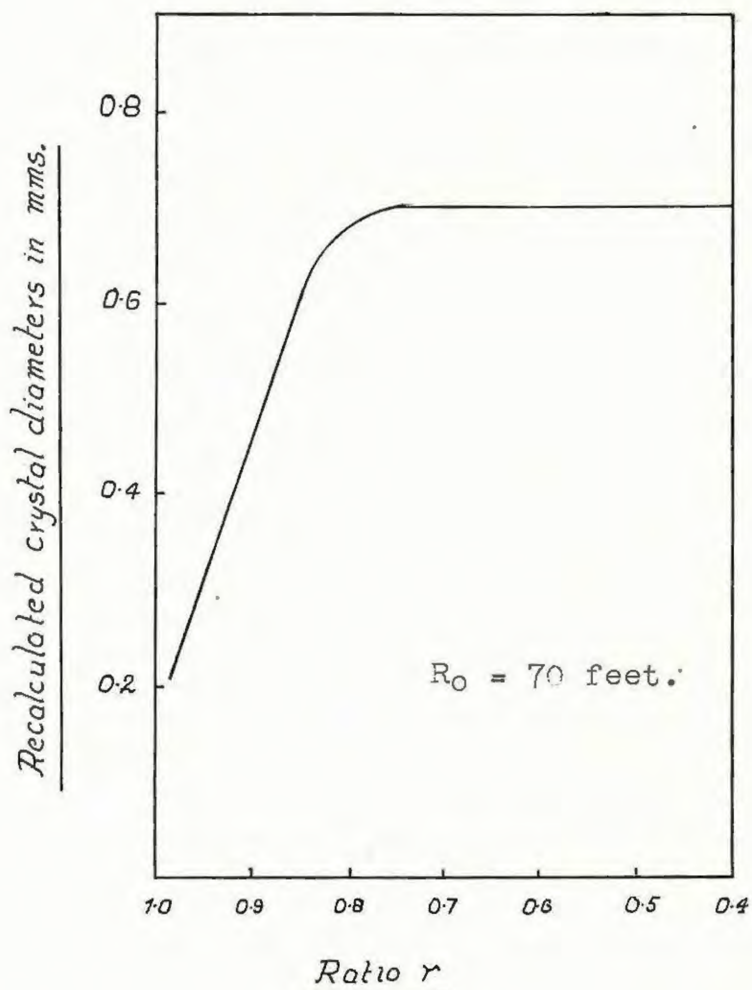

Fig. 3

Curve showing the variation in grain-size of plagioclase crystals with increasing distance from the upper contact. The minor irregularities have been smoothed out, and the distance from the contact expressed as a ratio $r = R/R_o$

where R_o = half total thickness

$R = R_o -$ distance from contact.

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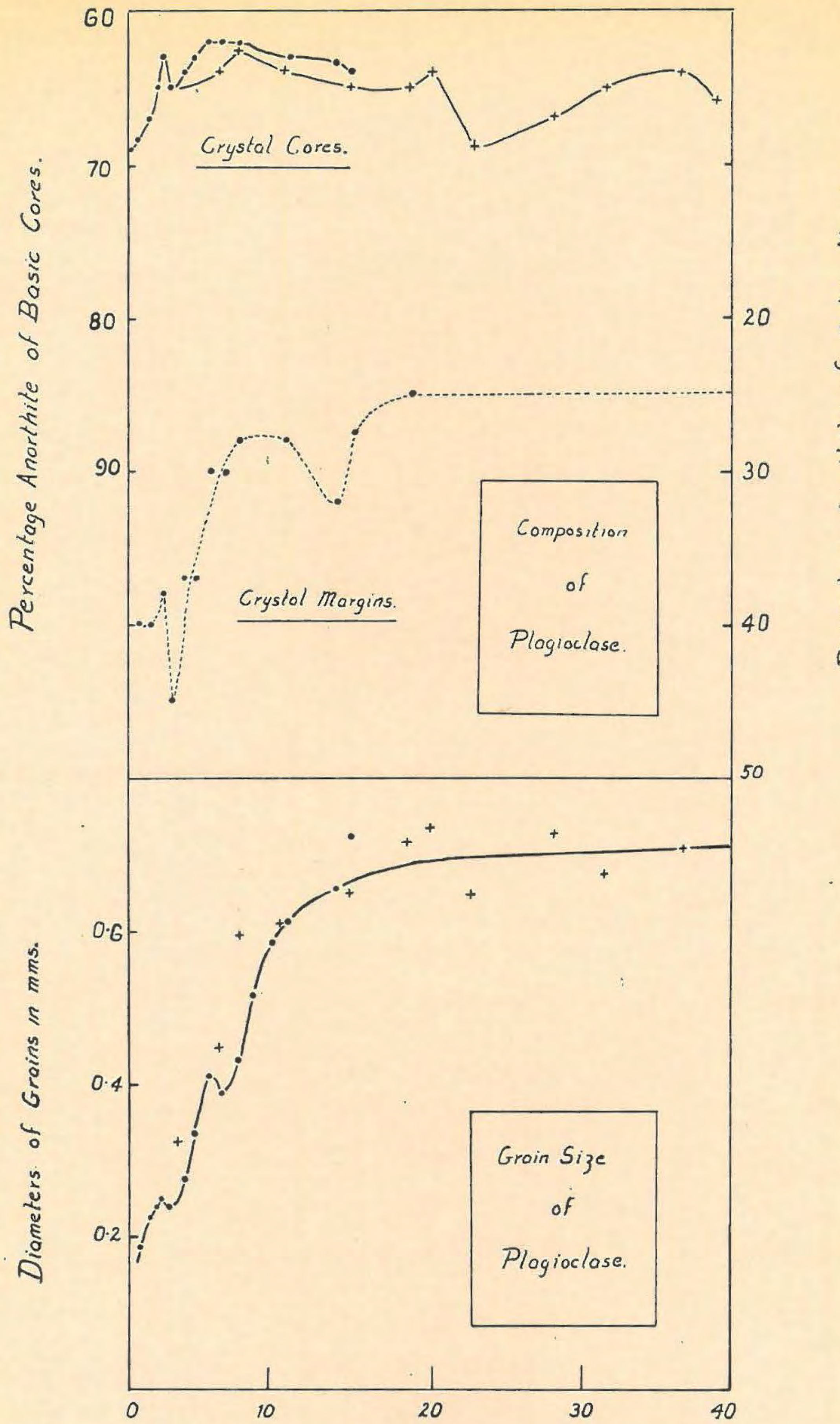

Fig.4.

Plots of two series of specimens representing two vertical sections a few hundred yards apart.

suggested that more detailed work might show a close correspondence between the grain-size and mineral composition, if the volumetric proportions of the zonal shells of different composition be quantitatively determined.

Range of Crystallisation.

It was hoped that the grain-size measurements could be used to determine the temperature range within which the felspar had crystallised, by the method suggested by Winkler (1949), but the results were not encouraging.

Winkler determined by measurement the variation of grain-size with distance from the contact, in the Cleveland tholeiite dike. By comparing this curve to a series of computed curves, drawn by combining calculations of cooling-velocities with experimental observations of artificial melts, he was able to determine the temperature range within which felspar, pyroxene and magnetite had crystallised. Certain basic assumptions made disregard the effects of convection, and latent heat of crystallisation.

The average curve obtained for the Khale Sheet (Fig.3) does not fall within any of his types, except in one case, which is that of a dike 12 feet thick, where the range of crystallisation temperatures is approximately 630-580 °C. The implications obviously have no significance, and this vigorous disassociation from the offered theoretical curves is probably chiefly due to the following facts:

(i) At the time of publication, Winkler had confined his attention to relatively thin dikes, to which the Khale Sheet is not comparable, being of horizontal attitude, and about 140 feet thick at the site from which the specimens were collected. It becomes obvious that more data are required for bodies of this size.

(ii) In larger, horizontal bodies, the effects of convection currents should be appreciable, allowing a low viscosity, and latent heat of crystallisation might play a significant rôle in the retardation of cooling-velocities.

(iii) The presence of numerous horizons of dolerite pegmatite indicates local concentrations of volatiles, a factor which would strongly influence crystal-size, and retard the initiation of crystallisation. It is this latter factor which is the chief cause of the variation in grain-size, for the specimens for which the measurements lie markedly above the average curve, usually have strong pegmatitic affinities, and even the naked eye can comfortably observe the fluctuations from one thin slice to another. The irregular location of the plots in the Fig. 4 is a reality, and not solely the fault of the measuring procedure.

Composition.

As discussed below, under the topic of zoning, the plagioclase is subject to great variation in composition. The composition of the basic cores, however, changes only slightly in different parts of the sheet, and it is interesting to note that, in some cases, there is a relation between small fluctuations in composition and grain-size.

The chief features of the Composition-Variation Curve are:

(i) The plagioclase is more basic in character at the margins of the intrusion, and becomes less basic away from the immediate chill zone. The phenocrysts have the same composition as the groundmass-felspars, but they are less conspicuously zoned.

(ii) In a few instances, the specimens whose felspars have average recalculated diameters falling below the grain-size trend indicated by interpolation between their immediate neighbours, are of a slightly more basic modal composition. Their basicity is reflected chiefly in the higher anorthite content of the cores of the plagioclase, and more rarely, the outer mantles. Micropegmatite is correspondingly deficient, and pyroxene relatively more abundant.

(iii) The cores of the crystals invariably fall between the limits of An_{61} and An_{69}, and only a small proportion does not lie in the field An_{63} - An_{66}.

(iv) Great variation in composition is present in the outer mantles of the crystals. This is discussed below under zoning.

Zoning of the Felspars.

The felspars of the intrusion are universally characterised by the development of a high degree of zoning: not a single thin slice examined showed felspars whose composition is the same in both the cores and the outer margins. Occasionally individual slides, or parts of slides, contain felspars whose composition varies by as little as 10% of anorthite, but these crystals are grouped in patches, or characterise certain horizons, and are not disseminated amongst the more strongly zoned felspars. The most frequent variation in composition from the basic core to the outer, acid mantle is of the order of 30-40% of anorthite, and occasionally variations of as much as 50% of anorthite may be observed, this generally amongst felspars of larger than average grain-size, or well beyond the influence of the upper and lower contacts.

A very small proportion of felspars shows reverse and oscillatory zoning.

The Fedorov Method of felspar determination being quite unsuited to the study of zoned crystals, measurements were carried out according to the Zonal Method of Rittmann (Chudoba and Kennedy, 1933). The method is reasonably accurate, and suited to the determination of rapid changes in extinction angle.

General Characters of Normal Zoning.

While the variable nature of the felspars does not encourage comprehensive generalisations, a number of practical observations may be noted, as descriptive of the character of the zoning in all parts of the sheet.

(i) In most cases the zones of varying composition are symmetrical about a central (OIO) twin plane, as in the case of Carlsbad or Complex Carlsbad-Albite twins, the zones of highest anorthite content being nearest the twin plane. Crystals which have the most basic zone located to one side of the central twin plane, are usually asymmetrical in shape or area about the twin plane; for the most part the (OIO) twin plane is equidistant, approximately, from the opposite crystal margins cut by the plane of the slide. A small percentage of crystals was observed to heve completely asymmetric zoning, and the outer margins of such crystals show, at opposite sides, differences in anorthite content of as much as 27 percent. In addition, the core of basic plagioclase in these types was found to be situated closer to the more basic margins than to the centre of the crystal. Such marked asymmetry is rare.

(ii) On the basis of the above observation, the average shape of a crystal with (OIO) and (OOI) vertical, may be contoured with lines of equal composition, to illustrate the type most frequently encountered(See Fig. 5). From this it is apparent that the change in composition in the direction perpendicular to (OIO) is more or less gradual and uniform until the more acid zones of composition less than An_{40} are reached, after which the change is rapid. Along the direction perpendicular to (OOI) the fall in anorthite content is much more gradual, until a critical point close to the margin is reached, after which the change takes place in a very narrow zone. Where the zone is not too narrow to defy accurate determination, it can be shown that the composition is as sodic as that along the perpendicular to (OIO).

The migration of the extinction shadows according to a definite plan in the normal types of zoning yields an easy method of determining whether the crystal under observation is cut through the basic core, or through a section displaced from the core. In the case of the latter, the extinction shadows move out from a central core which is square in shape, rather than rectangular.

(iii) The degree of albite enrichment of the outer zones is a function of the relative distance from the basic core, along any particular direction. Hence the most sodic zones are to be found furthest from the core. This is particularly apparent when the whole crystal is coated with an outer mantle of sodic plagioclase of approximately constant composition: small embayments in the enclosing minerals, such as pyroxene, which allow the crystal to grow locally to a greater width perpendicular to (OIO), are occupied by plagioclase of particularly high albite content. One such embayment, filled with plagioclase An_{16}, forms an extreme outer zone to a crystal whose core is of plagioclase An_{67}. It is not possible to define any absolute distance from the basic core which would correspond to a certain composition, for this distance varies as the grain-size varies.

(iv) It is a matter of common observation that the most sodic outer mantles are usually associated with micropegmatite. When this is the case, the outer mantle is generally not as free of minute, foreign inclusions as when the crystal's marginal growth is impeded by the presence of pyroxene. Contiguity between plagioclase and pyroxene does not always preclude the development of highly sodic outer zones, for these are common as in (iii) above. Some of the slices examined show a paucity of micropegmatite, and this is reflected in a series of felspars whose outer mantles are very much less acid than specimens from above or below that horizon. Mutually interference between felspar crystals is usually reflected in the relatively high anorthite content of the outer zones.

(v) Felspars with cores of high An content are generally less conspicuously zoned than those of average composition. A problem is imposed by the observation that in one slice examined, a small group of felspars has cores ranging in composition up to 69 percent of anorthite, with margins of only 48 percent of anorthite molecule, while only a matter of one or two crystal lengths away the more common types are encountered, showing zonal variation from An_{65} to An_{28}. It is not impossible that the low degree of zoning is due to obstructed crystal growth in the plane of the slide, but it seems most significant that these crystals should have the most basic cores yet encountered.

Oscillatory Zoning.

It can be shown that plagioclase felspars exhibiting oscillatory zoning are confined to the relatively narrow margin[5], which came within the cooling influence of the contacts, or occur as large phenocrysts in the lower levels of the intrusion. These are disseminated amongst felspars showing normal progressive zoning, and occur with a frequency of one or two per slide. In all slices cut from the specimens which were taken more than five feet from the upper contact, oscillatory zoning was not observed, except in the case of the near-basal specimens where the original phenocrysts are coated with an overgrowth in optical continuity. Such overgrowths show progressive zoning in their margins with advancing crystallisation.

This, in effect, implies that the conditions of rapid chilling were amenable to the formation, or preservation of this structure, and that the slower rate of cooling in the main body of the sheet had the opposite effect.

There appears to be no fixed number of anorthite-rich maxima within the crystals, variations being observed from commonly two up to six. The maximum anorthite content of the successive alternating zones is, however, often constant, notwithstanding that the successive shells are of variable thicknesses. This is not the case where partial repair has occurred. Outside of what may be termed the 'zone of alternating maxima and minima', normal progressive zoning lowers the anorthite content as in the common types. The outer mantle of sodic plagioclase is as albite-rich as before.

Although the change between maxima and minima of anorthite content is often gradational, where the shells are sharply demarcated, they are parallel to the clino- and basal pinacoids, and more rarely the prism faces. They do not appear to be parallel to the orthopinacoid, although the rarity of sharply demarcated shells does not allow this latter statement to be made with certainty. An irregular indentation of the clinopinacoid-zone surfaces indicates incipient resorption in these felspars of the lower horizons. That a certain amount of resorption has been a general feature here is indicated by numerous irregular streaks of differing extinction in most of the plagioclases.

The statement that felspars of the main bulk of the medium-grained rock show no oscillatory zoning may be modified by noting that, in about 35 slides, only one crystal was seen showing vaguely defined alternating shells, in which the positions of extinction differ by only a fraction of a degree.

Summary of Relevant Data.

The plagioclase felspars of the Whale intrusion are universally zoned. Normal or progressive zoning is the type most commonly encountered, and it is evident that those crystals which were permitted to grow unhindered by crystal interference, developed the most sodic outer margins. On the other hand, crystal growth impeded by crystal interference has resulted in less sodic outer mantles.

Crystals with the thinnest, most basic outer mantles are found in the horizons under the immediate cooling influence of the contacts. These horizons occasionally contain felspars which show oscillatory and rhythmic zoning, whereas the more slowly cooled horizons do not, except towards the base of the intrusion. Incomplete resorption of early-sunken felspars is evident in the latter horizons. There is no fixed number of anorthite-rich maxima in the various crystals showing oscillatory zoning, and the composition of the successive shells is always less anorthitic than An_{69}.

The composition of the cores of plagioclase crystals shows continuous variation with successive horizons, and there is a suggestion of sympathetic variation in composition of both cores and outer mantles with grain-size.

Conclusions.

The normal, progressive zoning of the felspars is quite in accord with the production of a residuum richer in alkalies, with continued crystallisation, when the rate of heat loss is such that continuous readjustment between the solid and liquid phases is not permitted. Thus the most acid plagioclase is to be found in the outer zones of the crystals, particularly in small embayments in contiguous minerals. There is no evidence to suggest that the highly albite-rich fractions did not develop in the immediate domain surrounding each crystal.

It is obvious that the same continuous process could not account for the phenomenon of rhythmic zoning, and that crystals showing this structure have had a more complicated history than those showing normal zoning. Phemister (1934) has summarised the various processes invoked to account for interruption of the steady decline in anorthite content from core to margin:

(i) Movement of crystals in the magma, whether by gravitative settling or by convection currents.
(ii) Movement of the magma as a whole into a region where different conditions of temperature and pressure prevail.
(iii) Irruption of additional magma into the crystallising liquid.
(iv) Loss of volatile constituents.

Phemister believes that the chief cause of oscillatory zoning is the periodic accession of hot magma into higher chambers in which crystals are forming, consequent on relief of pressure due to eruption. This mechanism is essentially embodied in (iii) above. He also offers the hypothesis that the thin, subsidiary zones of more calcic plagioclase are due to an autogenous process resulting from a lack of balance between the rate of growth and rate of diffusion. He describes the rhythm of events as:

(i) deposition of plagioclase with a much higher An:Ab ratio than in the magma, and concomitant concentration of albite in the liquor within the domain of crystallisation.
(ii) reaction of the crystal periphery with the more albitic liquor to form a less calcic plagioclase, and concurrent rise of the An:Ab ratio in the liquor both through reaction and through diffusion.
(iii) deposition of calcic plagioclase once more.

Mild objection to this hypothesis might be entertained on the grounds that we might expect to find oscillatory zoning on a fine scale to characterise the groundmass felspars of many dolerites and basalts, instead of being restricted to the phenocrysts or odd grains disseminated in the groundmass, which, from the literature, appears to be generally the case.

As pointed out by Phemister, were it not for the misleading implications of the term, the word xenocryst would best denote that these problematical crystals had lived a more complex history than those with which they finally retired. They are accidental inclusions gathered up by the magma in the process of emplacement, and the present writer believes that those of the Khale intrusion owe their structure to the cyclic repetition of events during the stage when the magma was being forced to its present position. That these events were indeed cyclic and reversible, must be inferred from the fact that in most cases the cores of the oscillatory zoned crystals are little different in composition from those of the progressively zoned felspars of the groundmass. The Khale Sheet is perhaps not a valid testing-ground for the hypothesis quoted above, the evidence of an abundant volatile content indicating that a high viscosity would not be a feature of the magma. Nevertheless, the presence of the structure still requires explanation.

It is significant that the variation in the successive shells is always to the sodic end, and away from the An 69 value which characterises the cores of the most basic felspars. Thus, when the physical and chemical conditions were such that the magma was saturated with plagioclase of that composition, it was in what might be considered the normal state. Any cause of departure from this normal state must be looked for in terms of separation of aless calcic plagioclase, and oscillation as due to a periodic return to the normal state.

As the liquidus-solidus to temperature relationship is so shifted as to cause most calcic plagioclase to be deposited in the presence of a high volatile content, at a constant temperature, the normal state of this magma might be considered as one in which there is a high concentration of volatiles. The following facts support this belief:

(1) The modal composition of the typical rock-type

is intermediate, in nearly all respects, between the Downes Mountain type, and the Dolerite Pegmatite type, the latter a rock which owes much of its characteristics to a high volatile content.

(ii) There are present numerous bands of dolerite pegmatite, up to six feet thick, and abundant hydrothermal veinlets in both the dolerite and the country rock.

(iii) Uninverted pigeonite is present both as phenocrysts and crystals in the groundmass. Walker and Poldervaart (1949) consider volatiles to act as catalysts in the preservation of pigeonite.

(iv) Amphibole is present in rather more than usual amounts in all parts of the sheet.

On the strength of the support of so many different factors, the present writer is inclined to accept the last of the four main processes outlined by Phemister as the most likely to have governed the production of oscillatory zoned felspars. It would not be wise at this juncture to express a specific opinion as to the cause of the repeated draining and re-infiltration of the volatile constituents. Two factors should, however, be borne in mind. The first is that loss of volatile content is theoretically capable of causing a more sodic plagioclase to be deposited at the same temperature. Secondly, the sheet, in its present position, shows that upward migration of the volatiles subsequent to intrusion appears to be a natural phenomenon. Thus, pegmatitic rock is most common to the upper levels of the sheet. This process also partially explains the incomplete resorption of earlier felspar crystals in the lower horizons, as the early loss of volatiles would cause the magma to be saturated with more sodic plagioclase, thus bringing to a halt at an earlier stage the tendency to resorb basic plagioclase.

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Explanation of Fig.5.

The sketches are of different types of felspar crystals as seen between crossed nicols, the zoning being indicated by the varying densities of shading. The accompanying graphs indicate the changes in composition across the crystals. Intercepts along XY are in all cases proportional to distances along AB.

No.

1. Normal progressive zoning of crystal from basic core to acid mantle. Zoning symmetrical about central (OIO) twin plane. Type most common.

2. Of type similar to No.1., but in which the basic core is asymmetrically situated. Type uncommon.

3. Progressive zoning, where the successive shells tend to be sharply demarcated, otherwise type similar to No.1. Type not common.

4. Type in which the basic core is close to the crystal margin, and opposite margins are of vastly different compositions. Type rare.

5. Crystal showing oscillatory zoning, in which the increase in anorthite content in successive shells is gradational. Type exceedingly rare, and confined to contact zone.

6. Crystal showing rhythmic zoning, with the change in successive shells normally sharp. Type not uncommon in the contact zone.

7 and 8. Sketches of felspars crystals to illustrate location of contours of equal composition in sections passing through the basic cores, and sections slightly displaced from the basic cores, respectively.

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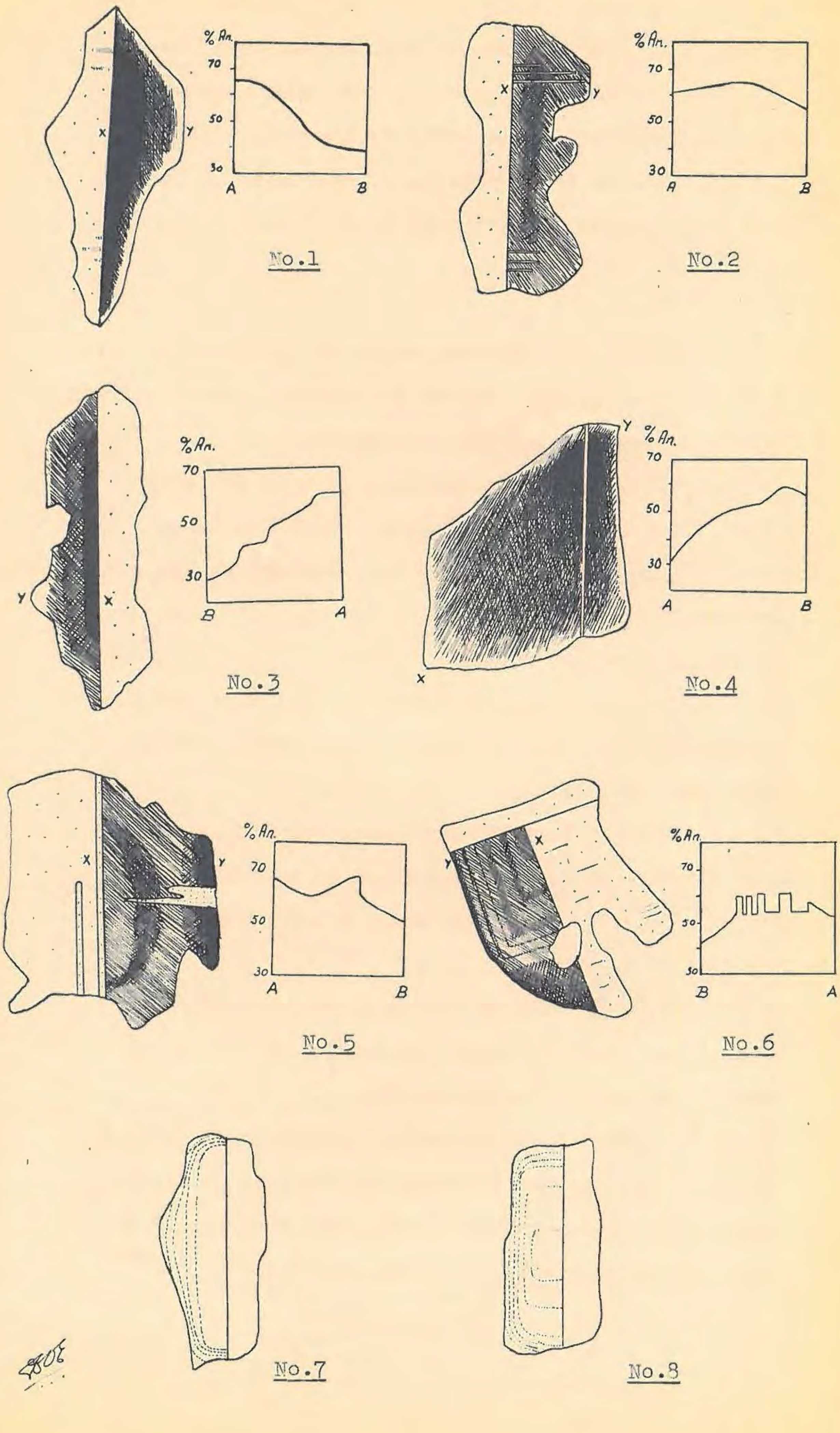
Fig.5 Types of Zoning in Plagioclase Crystals.



Clouding of the Felspars.

Previous Work.

The phenomenon of clouding in felspars has been mentioned in passing by various authors as far back as 1877, and has been connected with the effects of contact metamorphism by some since 1888.

In 1928, R.A.Daly made reference to clouded felspars in felspathised quartzite xenoliths within the granophyric quartz-syenites above the main norite zone of the Bushveld Igneous Complex, Transvaal. It is not, however, clear whether the clouding mentioned refers to alteration by sericitisation, or the type in question. In view of the nature of the felspars, soda-orthoclase and oligoclase-albite, it probably does not.

A collation of the facts was made by MacGregor and his findings published in 1931. This paper deals with:

'.......a characteristic effect that is often produced in the fresh plagioclase felspars of igneous rocks by thermal metamorphism, namely, the development of a special type of cloudiness caused by the appearance of minute inclusions. Reference is also made to certain well-known rocks in which the clouding of plagioclase felspar has been described without any suggestion that the peculiarity of the felspars is connected with thermal metamorphism.(Abstract)

Furthermore,

'.......it should be understood at the outset that the peculiar cloudiness of the felspars(of contact metamorphosed igneous rocks) is in appearance quite different from any turbidity due to decomposition.'

The aspects of the clouding dealt with by MacGregor might be summarised as follows:

(1) In the intermediate and inner zones of contact-aureoles thermal metamorphism has often, but not invariably, produced in the fresh plagioclase felspars of lavas and minor intrusions a form of clouding due to

the development of minute inclusions.

(ii) When the felspars have been completely recrystallised, they are unclouded.

(iii) The clouding is more often than not restricted to the more basic portions of zoned crystals.

(iv) The clouding is thought to be due to a high degree of heating during thermal metamorphism. The possibility of pneumatolytic or autopneumatolytic action is not ignored, but MacGregor prefers to believe in the former process.

Several references to clouded felspars of this distinctive type have been made by Doris Reynolds, noted during her examination of the Newry Complex, and the metasomatism of quartzites at Kiloran Bay, Colonsay. Reference will be made to these later, but for the moment suffice it to say that she quotes evidence of clouding being produced by mechanisms other than heating.

<u>Felspars of Khale Sheet</u>.

While no peculiarity can be observed in the hand-specimen, due to the dark colour of the rock as a whole, one of the most distinctive features of the same specimens as seen between slide-glass and coverslip, is the development within the felspars of what is aptly termed clouding. Under low power objectives, the otherwise colourless silicate becomes brownish, or buff in colour.

It must be admitted that little was learned regarding the compositional nature of the cloudy effect during a more careful examination. Microchemical procedure according to the method of Brammall, (see A.Holmes, 1921) yielded either no reaction for iron, or at best, an unconvincing yellow discoloration.

Optical examination is best carried out using a No.7 Leitz objective, as with a 1/12 inch oil immersion lens the overlapping lines of the Becke Effect dominate the field. Clearly the clouding is not due to opaque inclusions, although a very small proportion of the minute inclusions is sometimes composed of opaque specks which are in all probability iron ore. Moreover, it was found that the great majority of the inclusions that could be resolved are irregular, rod-like or comma-shaped granules of a pale green to colourless, transparent mineral, which the author suggests is secondary amphibole, or possibly epidote. These are anisotropic, with a refractive index considerably higher than that of the host plagioclase, but a more detailed examination of their optical properties is ruled out by their minute size. Layer upon layer of the granules can successively be brought into focus within the thickness of the crystals in the slide, and hence, for all practical purposes, they extinguish with their host. Slightly beyond the position of extinction, those in focus can be seen to be anisotropic. It is perhaps significant that localised areas of heavy clouding within a single large crystal are areas of strain, about which the migrating extinction shadows of the zoned felspars bend in a marked manner.

The distribution of the areas of heavy and light clouding is problematical. After a first examination the observer is tempted to accept, simply, that some felspars are clouded, while others are not, and that the distribution of the areas of clouding within a single crystal follows the same rule. It is, however, well known (see MacGregor) that in zoned crystals the phenomenon is mostly restricted to the calcic cores of the felspars, while the sodic margins are clear. This is very clearly illustrated in the Khale intrusion. As observed by MacGregor and Doris Reynolds, there is a relation between the density of clouding and multiple twinning, the granules tending to group themselves so as to rule lines parallel to the composition planes. In addition, some crystals examined by the author showed only alternate twin lamellae to be clouded, the intervening areas being only lightly dusted.

What is considered to be the most significant feature of all, is the fact that dense clouding is found only in the horizons immediately adjoining the contacts, that is, within 12-14 feet of the granite into which the dolerite is intrusive. The phenocrysts are perfectly clear. Clouding is seen to be persistent in all parts of the intrusion, but in the main body takes the form only of a light dusting within an occasional crystal. The felspars of the pegmatites often show quite marked brown tints. Doris Reynolds refers to a paper (not available to the writer) by D.S.Belyankin, in which is described a gabbro-diabase dike intrusive into granite at Cape Medvezhy, White Sea, Russia. Here the younger intrusion is characterised by cloudy felspar in the marginal parts.

In the Khale intrusion, the author interprets the density of clouding as being related to the differentiated degree of zoning, as the marginal parts of the sheet are those containing felspars whose outer mantles are not highly sodic, and are at the same time very narrow. Towards the main body of the intrusion the outer zones of the felspars become more sodic, together with an increase in absolute thickness.

Further evidence comes from the thin slices showing the very common features of both clouded and unclouded felspars close to one another. It has been mentioned that the composition of the outer mantle is highly variable within a single thin slice, and in these cases theres is a strong suggestion that the felspars which are most densely clouded, are those which have the least sodic outer mantles, or have the thinnest outer mantles. Such a relation obviously cannot be proved empirically by thin section microscopy, the plane of a thin section representing only a thin cross-section of a part of the crystal, but a considerable degree of reliance may be placed on the appearance in thin section when it is realised that the clouding is in itself a local feature which rarely affects the entire crystal. The implication follows that the outer, sodic zones play the rôle, not only of areas unsusceptible to clouding, but actually of protective envelopes. As the crystallisation of pyroxene and felspar goes on side by side during the middle stages of magma consolidation, many of the pyroxene crystals are directly in contact with the basic zones of the felspars. This fact assumes importance when the rôle of the acid mantles is recognised, for it was found , in the above cases, that the clouding is often densest around the pyroxene obtrusions. In addition, these are also areas where marked strain is apparent, the extinction shadows bending in concentric fashion about the muzzles of the pyroxenes, which frequently show alteration to secondary amphibole in all stages from incipiency to the complete. In short, the pyroxene appears to have played the part of a bridge or channelway through the acid mantle, to the basic plagioclase cores.

In more than one case, where two plagioclase crystals have grown side by side, in such a fashion that no space has been allowed for the development of sodic outer zones, a broad strip of clouding can be seen to cross the margin and continue unchanged in direction into the adjacent crystal.

Another clue is offered by the occasional observance of the secondary amphibole grading in streamers of granules of ever-decreasing size into the felspar, where the orientation is such that the 'ruled line' nature of the clouding parallel to the composition planes of repeated twinning is demonstrated.

Conclusions.

It is known that, in spite of the close similarity of the crystal-structures of albite and anorthite, and the comparable ionic radii of the Na. and Ca. ions, there is a difference in the dimensions of the unit cell of the two structures. According to Taylor (see W.L.Bragg, 1937), the dimensions of the unit cell are:

	a	b	c
albite	8.14	12.86	7.17
anorthite	8.21	12.95	14.16

The length of the c axis is shown to be doubled in the case of the anorthite structure, but it is uncertain whether there is a continuous increase in the distortion of the lattice with increase in anorthite molecule, or whether there are two alternative structures which change abruptly from one to the other with a critical calcium content in the intermediate felspars. Taylor inclines to the latter view, and infers tentatively that this change implies a further distortion of the tetrahedral framework from the albite form, due to the different co-ordinate numbers of calcium and sodium.

If this distortion of the lattice increases the defects within the crystal lattice, it is then possible that the albite structure offers a greater resistance to the migration of foreign material through the lattice, than does the anorthite structure. This process of diffusion over small distances within the felspars would presumably occur while the body was still hot, for the disorder within the lattice is dependant on temperature, a feature discussed by Buerger (1948). A threshold value of 0.8-0.9 of the absolute melting-point temperature, below which diffusion will not occur in silicates, is given by Eitel (see Bowen, 1947). It is pointed out by Bowen that the threshold value is strongly influenced by defects due to strain and rapid crystallisation, and diffusion will thus be permissible at a much lower temperature.

A statistical examination of chemical analyses by MacGregor shows that the series oligoclase-anorthite has an iron content very often much higher than that of albite, and this he ascribes to a higher original iron content after crystallisation. It is, however, also possible that a high iron content in basic plagioclase is produced by the easier ingress of ions into the lattice following on initial crystallisation. Furthermore, the concept fails to explain why all plagioclase crystals within the same thin section are not equally clouded, why only the felspars of the contact zone and the pegmatites are clouded, or the relation between the density of clouding and presence of sub-poikilitically enclosed pyroxenes.

The evidence of the thin sections, to which ideas on ionic migration are not averse, leads the writer to believe that the clouding of the felspars is due to late-magmatic or deuteric-stage migration of the necessary material into the felspars. The clouding of the felspars of the dolerite pegmatite is then explained by the essentially contemporaneous crystallisation of the pyroxenes and felspars, thus effectively breaching the gap between pyroxene and the basic cores. There followed the growth of minute granules of secondary amphibole or epidote, which at the same time set up conditions of strain in the host material.

Regarding the source of the migratory material, there is a large number of processes characteristic of the later, cooling stages of consolidation, any one of which could have been active. Chief amongst these might rank exsolution processes in the pyroxenes during cooling, and residual concentration of iron in the deuteric stage.

Thus, while MacGregor believes that the phenomenon is in many cases due to intense heating during thermal metamorphism, the clouding of the felspars of the Whale Sheet may here be ascribed to a different cause. It might be mentioned that Reynolds (1936) describes an olivine-monzonite from the Newry Complex, in which the plagioclase is clouded by a fine opaque dust, suggested to be iron ore. The alkali-felspar, soda-orthoclase, is also clouded, but this clouding is of a slightly different character. She comes to the conclusion, in the case of the rocks concerned:

'.......the clouding is due to the migration of material after the felspars, quartz-felspar symplectite and biotite had concluded completed their growth.

and

'It is, however, impossible to correlate clouding (in this case) with contact metamorphism.'

...._....

<u>Note</u>. In a personal communication to the writer, Dr. A. Poldervaart has indicated that his own work has led him to believe that the feature of clouding is due to the introduction of material by migration. No further details are given. He announces that a paper dealing with the topic will shortly be in print.

Explanation of Plate IV.

Fig.1.

Clouded felspars in a specimen taken at five feet from the upper contact. Ordinary light (X 36).

Fig.2.

Same as Fig.1.

Fig.3.

Photomicrograph illustrating nature of the clouding, as seen under high power objectives. Notice the area of darkest clouding is adjacent to pyroxene. Ordinary light (X 130).

Plate IV.

Fig.1.

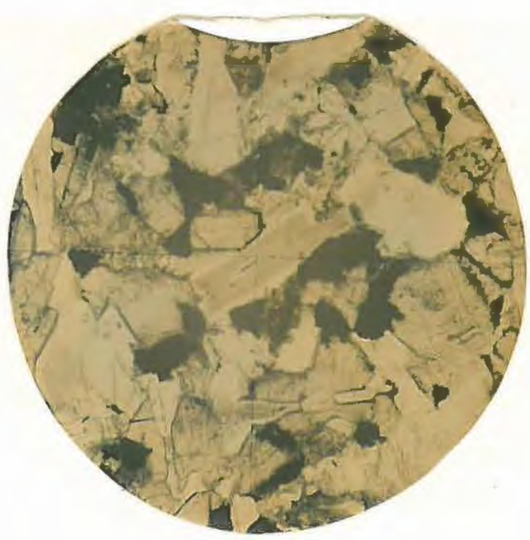


Fig.2.

Fig.3.

Explanation of Plate V.

Figs.1 and 2.

Felspar crystal showing the relation between normal progressive zoning and the density of clouding. Crossed nicols and ordinary light (X 165).

Figs.3 and 4.

Specimen near basal contact illustrating the linear character of clouding parallel to the composition planes of polysynthetic twins. Crossed nicols and ordinary light (X 43).

Plate V.

Fig. 1.

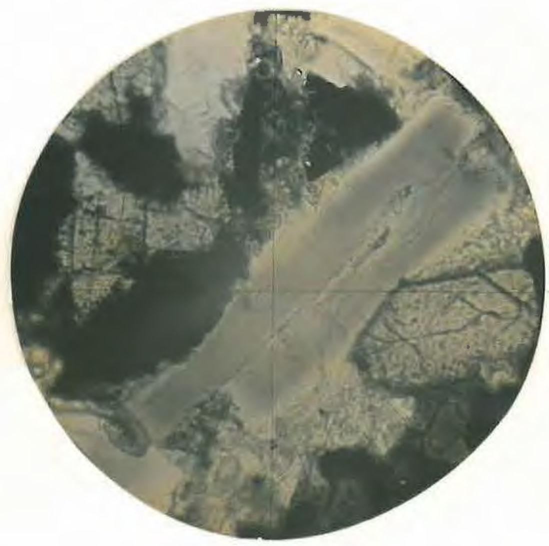


Fig.2.

Fig. 3.

Fig. 4.

THE PYROXENES.

Introduction.

Although the pyroxenes show a number of interesting features, they do not offer themselves for satisfactory study, as the effects of hydrothermal action tend to dominate certain horizons, while most show the impress of incipient alteration. Many specimens not affected by atmospheric weathering, such as those from the quarry, are so highly altered to secondary material as to obscure the orthomagmatic relations, and as such, are useless for study. Most basal-contact specimens have the pyroxene more or less completely pseudomorphed by amphibole and serpentine-chlorite.

Optical examination was carried out using the universal stage, and refractive indices determined by immersion methods. The determinations were carried out chiefly with a view to finding compositions, rather than supplying full data.

Pyroxenes of Medium-grained Dolerite.

Two clinopyroxenes are present, pigeonite, and augite of rather low 2V angle. Orthopyroxene is absent from the main body of the sill.

Pigeonite.

The pigeonite most commonly forms columnar and curving cores to the augite, the habit being suggestive of an earlier onset of crystallisation. Occasionally the pigeonite is set in the marginal zones of the augite, and may even exist as discrete grains enclosed by the plagioclase, but the first-mentioned habit is dominant. Where discrete grains exist, a high degree of idiomorphism may be shown. While some of the earliest pigeonite may have preceded the plagioclase in initiation of crystallisation, the subophitic relation between the pigeonite protruding beyond the augite mantles, and the felspar, is indicative of a later cessation of crystallisation. Thus plagioclase ophitically penetrating augite does not normally indent the pigeonite in the centre of the compound crystals, but the relation between them is subophitic towards the tapering ends of the crystals.

In the main body of the sheet, this early pigeonite is quite distinctive in appearance, and perhaps better picked out in plane light. Whereas the augite is pale brown in colour, the pigeonite is colourless and characterised by curved fractures which are emphasised by their being filled with dark granular material. There is a resemblance to a grub within a nut. Towards the roof the pigeonite approaches the augite more nearly in colour. The pigeonite is markedly elongated along the c axis of the augite, and the cleavages and partings appear continuous. Attractive herringbone structures resulting from a combination of the basal parting and (100) twinning are extended into the enclosing augite. Twinning is achieved by simple symmetrical growth about the (100) plane, and it is interesting to note that the enclosing augite follows on this twin plane, which is merely extended as a plane of symmetry into it.

In all cases examined there is an unchanging relation between the optic vectors of pigeonite and the enclosing augite, except where the outline of the former shows deep embayments or is crudely serrated: in such cases there is no relation between the optic vectors. In the common case, the Z vibration-direction of both is continuous, while X and Y are interchanged. A simultaneous separation of a few degrees is permissible to allow for small changes in extinction angles. Rarely may be found enclosed in the same augite crystal, both columnar pigeonite with the optic vectors fixed in the manner described above, and pigeonite of irregular, rounded shapes bearing no recognised orientation relative to that of the host. Between crossed nícols, in sections with an optic axis near vertical, small differences in birefringence are more easily seen, and the cores more easily picked out. The low 2V angle for much of the pigeonite is reflected in a very close approach to total extinction on rotation about X (or Y of the augite), as Z is brought to the vertical position.

The boundary between pigeonite and augite is undoubtedly sharp and well-defined in most pyroxenes, but it is common to find apparently gradational contacts where the host shows signs of uralitisation. In such cases, the loss of sharp margins is due to secondary material masking the discrimination, for the augite shows an ill-defined clouding and a shimmer effect in plane light.

In general, the pigeonite seems to have offered greater resistance to the process which effected the uralitisation of the augite, but, where altered, becomes a translucent to greyish-brown mass, the decomposition being most conspicuous along the curved fractures. Parallel with the deepening of colour of the unaltered pigeonite towards the roof, the alteration-product changes towards the greenish, secondary amphibole usually associated with the augite.

Augite.

The augite is the dominant pyroxene. When fresh, it is pale brown in colour, and non-pleochroic, although hydrothermal action in the initial stages may turn it either green or semi-translucent brown. Near the upper contact, the pyroxene granules develop an irregular purple mottling, which is associated with a sharp local decline in optic axial angle.

The habit of the augite alters slightly from one horizon to another, generally between the subophitic and poikilophitic of varying degrees of perfection. The poikilitic enclosure of small and well-shaped plagioclase laths is common, but the larger plagioclase crystals have limited penetration. Most specimens have a sprinkling of idiomorphic augite, generally of smaller grain-size than most. In common with many dolerites, polysomatic aggregates are encountered.

As with pigeonite, twinning takes the form of simple (IOO) twins, but in addition, these may occasionally be repeated, and uncommon twins repeating on the basal plane may be seen. Herringbone structures are well developed, and parting parallel to (IOO) and (OOI) almost invariably accompanies the prismatic cleavage, as does a coarse parting parallel to (OIO).

Optic Axial Angle.

Certain of the optical properties are worthy of note by virtue of their variability. Although several scores of measurements of 2V angle were carried out by direct rotation about the optic normal, from one optic axis to the other, there appears to be little consistency of value either in a single thin slice, or within a single grain, except within a wide range. This is the outcome of their zonal nature.

In all pigeonites the 2V angle is highly variable, and most commonly increases from core to margin, although the reverse is also found. With the optic axial plane perpendicular to (010), 2V angles were noted varying between 9° and 24½°, but usually nearer the mean in the cores. The dispersion is noticably r > v. A small amount of near-uniaxial, possibly late pigeonite may be observed either in the outer rims of the augite, or as discret, xenomorphic crystals. In appearance these are very similar to the pale-brown augite, but have low 2V angles in the plane perpendicular to (010).

Where the augite does not enclose pigeonite, or encloses pigeonite with the optic axial plane perpendicular to (010), the 2V angle in the most common case increases continuously towards the margins of the augite, or may pass first through a minimum. Less frequently, the 2V angle shows a continuous slow decrease towards the margins. There is a fairly limited field defining the most frequently encountered lower limits of 2V angle, between 38° and 42°, but zonal variation may lift this angle continuously up to 49°. Angles as high as 60° were noted, but this is associated with a high degree of hydrothermal alteration. The lowest 2V angle encountered for augite in the more slowly-cooled dolerite was 34°. In all cases, the dispersion is always weakly r > v. Variations of 2V in augites and pigeonites are illustrated in Table 4.

In view of recent discussions debating a miscibility gap between calcium-poor and calcium-rich clinopyroxenes, separating pigeonite and augite of low 2V angle into two cotectic phases (Hess, 1941; Poldervaart and Hess, 1951; Kuno, 1950), it is interesting to note here the variation of 2V angle in pyroxenes within the zone where the drop in grain-size towards the upper contact becomes appreciable. These pyroxenes do contain cores of pigeonite with the optic axial plane perp-

Table 4.

	Pigeonite Core	Augite, successive mantles.
1.	9°	40° , 34°.
2.	14°	44°.
3.	small	40° , 45°.
4.	24° , 20°	no mantle
5.	no core	35° , 34° , 38°.
6.	" "	39° , 34° , 44°.
7.	" "	41° , 38° , 40°.
8.	" "	38° , 47°.

endicular to (010), exhibiting much the same 2V values as above, but more commonly the 2V angle of the augite increases concentrically about a number of different nuclei within the same crystal. The nuclei, in number up to three and four, are seen to be minute granules of pigeonite, of low 2V angle, which differ from those previously described in that the optic axial plane is parallel to (010). The cores may be uniaxial, or even biaxial in the plane at right angles to this. In the zone surrounding these minute pigeonites, the optic axial angle of the augite falls well below the previously noted values, and may equal 32°, the limit defined for augite by the first of the above authors. A small, but significant number of measurements showed that indeed the optic axial angle of the augite may be one degree less than the defined limit. It is possible to measure a continuous fall in 2V angle from margin to core of from 40-50° to at least 32°. At the same time the pigeonite values are higher, and some appear almost to bridge the gap. The following measurements were made on the universal stage, in monochromatic light, applying the necessary angular corrections with care:

Table 5.

	Pigeonite Core	Augite, successive mantles.
1.	$28\frac{1}{2}^{\circ}$	38° , 37° , $44\frac{1}{2}^{\circ}$.
2.	$23\frac{1}{2}^{\circ}$, 29°	39° , $45\frac{1}{2}^{\circ}$.
3.	$22\frac{1}{2}^{\circ}$	31° , 38° , 39°.
4.	19°	32° , 35° , 37° , 49°.
5.	no core	33° , 39° , 43° , $50\frac{1}{2}^{\circ}$.

It may be noted that the zone of low 2V values is small relative to the greater volume of the augite crystals showing higher values.

Whether or not there is an unbroken variation through pigeonite to augite is doubtful, as in all cases the zones examined are exceedingly narrow. It can confidently be stated that not in a single case was a broad zone, or significant area of a grain cross-section encountered, which showed a slow, continuous decrement across the 32° limit to values in the pigeonite field. The most careful measurements, however, indicated that some of the 2V values for augite may be as low as 31°. Kuno (1950) describes completely gradual zoning between pigeonite and augite, which are comparatively rich in iron,and accepts complete gradation between the two under both the intratelluric and effusive conditions. He points out that the rarity, or apparent absence, of pyroxenes with 2V angles in the region of 30° may be due to the flat shape of the lower part of the solidus curve in a solid-solution system with a minimum. As such, pyroxene with 2V angles in this field might be expected to be found as exceedingly narrow zones in zoned crystals.

There is a tendency for 2V angles between 35° and 38° to be more frequently encountered towards the upper parts of the sheet than in the lower.

Extinction Angles.

In a series of slices from different heights in the intrusion, c/Z angles of augite were measured as accurately as possible on (100) twins, according to a method described by Hess (1949). As far as possible, zoned crystals were rejected, and the most consistent values, measured in augite cores not enclosing pigeonite, were accepted.

Of twenty nine measurements from different horizons, fifteen showed c/Z angles between 43° and 44°, of which the majority were 43½°. A further seven showed a maximum deviation from this mean by 1½°. The highest and lowest values, deviating from this by some 2½°, were associated with abnormal zoning or signs of hydrothermal alteration.

In general, the values are most constant in the upper parts of the shbet, and those in the lower half have slightly lower values relative to the mean. There is sometimes a tendency for the extinction angles to increase from core to margins of the zoned crystals, the greatest variation being from 43° to 44½°.

The uniform extinction of compound crystals of pigeonite and augite sectioned parallel to (010) indicates similar values of extinction angle for the former.

Refractive Indices and Composition.

Refractive index determinations carried out on pyroxenes from different heights in the intrusion showed variation only within a limited field. For deducing the composition, the Y index of the augite was determined on (100) parting fragments showing an optic axis near the centre of the field of view, thus allowing an accurate check of orientation. By this method the Y vibration direction could be oriented N-S by exactly splitting the field with the E-W isogyre.

The following represents an average of values for augite of low 2V angle:

X : 1.696

Y : 1.699 Z-X : .025

Z : 1.721

Deviation from the lowest refractive indices measured indicates change of refractive index in zoned crystals.

The following is an average of Y index values for the low 2V augite (cores) at different horizons:

Height below contact.	Y Index.
3 feet	1.702
10 "	1.701
20 "	1.698
40 "	1.697
70 "	1.698
110 "	1.698

There appears to be a slight upward increase in the atomic percentage of iron. Pyroxenes of basal specimens are too highly altered to allow of accurate determination.

The composition, as deduced from the curves of Hess (1949), varies in the cores of the augite crystals from $Ca_{33}Mg_{42}Fe_{25}$ to $Ca_{31}Mg_{38}Fe_{31}$, the compositions being expressed as atomic percentages. For this, a constant 2V angle of 39° was taken, as it would be meaningless to do otherwise with its variable nature being kept in mind.

The deduction of the composition of the pigeonite is perhaps less reliable, as it is virtually inseparable from the augite by normal mechanical methods. In the procedure adopted for crushed fragments, the extreme rarity of suitably oriented flakes renders the determination of the Y index impracticable. For the determination of the Z index, the colour offers the best, if hazardous method for the distinction from augite. The Z index may be deduced as varying from 1.720 (Becke test applied to the compound crystals), to 1.726, as measured in immersion media. Thus the larger grains of pigeonite with the optic axial plane perpendicular to (010) range approximately between $Ca_6Mg_{57}Fe_{37}$ and $Ca_{10}Mg_{49}Fe_{41}$, as deduced by reference to curves of naturally occurring pigeonites (Hess, 1949). Those with the optic axial plane parallel to (010) will obviously contain more lime, but their minute, granular nature defies any separation.

Clear examples of graphic or lamellar exsolution of one pyroxene phase from another are absent from the intrusion. As the thickness is a maximum of about 150 feet, this is to be expected. The inability of some of the augites to attain total extinction in any position on the universal stage, probably represents, as suggested by Poldervaart and Hess (1951), exsolution on a cryptographic scale. The pyroxenes under consideration show, at best, only anomalous blue in lieu of total extinction. Reference to the stability relations of pyroxenes(Walker and Poldervaart, 1949, Table 9), indicates the magma from which the pyroxenes crystallised was initially above 1110°C, and relatively 'wet'.

Plate VI.

Zoned augite crystal with an embayed inclusion of pigeonite (black) in the core. The separate areas of pigeonite are in optical continuity, augite of low 2V angle occurring between them. Crossed nicols (X 33).

Pyroxenes of Chilled Contact Rock.

Where the groundmass of the basaltic contact rock is capable of being resolved, the habit of the augite is seen to vary between that of stumpy granules and feathery or radiating intergrowths with plagioclase. Attractive examples of graphic intergrowths between the two minerals may be seen.

The chief interest attaches to the microphenocrysts of the almost glassy contact rock. A series of slices taken between one quarter of an inch and two inches from the upper contact shows that the groundmass has an ill-crystallised, mottled appearance, the latter feature due to the segregation of dark circular patches separated by lighter-coloured material. Set in this indefinite groundmass are abundant microphenocrysts of pyroxene and plagioclase. These may show a high degree of idiomorphism as separate crystals, but when they form part of a glomeroporphyritic aggregate, crystal faces are poorly developed. While the bladed plagioclase laths may reach lengths of one millimetre, the pyroxenes are generally one tenth to one half of this size.

Two clinopyroxenes are present as microphenocrysts, pigeonite and augite, the former being more abundant. The occurrence of pigeonite in this form is worthy of attention, as it is apparently very uncommonly found as such. A single colourless crystal of pyroxene enclosed by augite showed a negative optic axial angle of 70°, and is probably orthopyroxene.

The pigeonite occurs both as anhedra enclosed by augite, and as separate euhedral crystals. In the former case the margin between the two minerals appears to be sharp. Pigeonites withthe optic axial plane both parallel and perpendicular to (OIO) were examined, but the latter is easily the most frequently encountered. The following figures indicate the range in optical axial angles:

Table 6.

Pigeonite Core	Augite, successive mantles.	
1. 4^o-20^o (O.A.P. in (OIO))	38^o- 40^o.	) uncommon.
2. 3^o (" " ")	34^o- 43^o.	
3. 25^o (O.A.P. perp.(OIO))	$33\frac{1}{2}^o$.	)
4. 20^o (" " ")	$34\frac{1}{2}^o$.	)- common.
5. 20^o (" " ")	no mantle	)
6. $17\frac{1}{2}^o$ (" " ")	no mantle	

Refractive indices were determined as:

Y : 1.695) 2V : 15^o- 20^o.
Z : 1.717

The composition, as deduced from the curves of Hess, is $Ca_7Mg_{57}Fe_{36}$.

Augite occurs as discrete crystals, in appearance similar to the pigeonite. The optic properties indicate it is little different from the early augite of the main body of the sheet. The Y index of 1.693 shows the composition is near $Ca_{35}Mg_{45}Fe_{20}$.

In view of their small size, and slight differences in composition from the pyroxenes of the medium-grained dolerite, the microphenocrysts are probably not true early intratelluric phenocrysts. It is, however, an interesting indication that pigeonite started its course of crystallisation in the early stages of consolidation.

Pyroxenes of the Dolerite Pegmatite.

The pyroxenes of the dolerite pegmatite are characteristically feather-like in shape, and may reach lengths of several centimetres, while having a breadth of only a few millimetres: stumpy, columnar crystals are also common. Radiating, bifurcating aggregates of crystals may show, under the microscope, that the (100) twin plane is markedly curved, and the extinction of any one individual thus non-uniform.

Augite and pigeonite are both present, the latter being more obvious than in the normal dolerite. Pigeonite occurs both as cores to the augite, and discontinuous outer mantles to it, as well as discrete crystals. The augite shows faint pleochroism in shades of pale yellow. While hydrothermal action has been vigorous, much of the pyroxene is quite fresh.

Measurements of optic axial angle show little difference from the values for pyroxenes of the normal dolerite, with a possible exception that a greater proportion of the crystal cores has values lying between 42° and 46°. The fluctuation of 2V is just as rapid and anomalous, values often changing concentrically about a number of different nuclei in the same crystal. Determinations of refractive indices of pyroxenes in a pegmatite with an unusually high colour ratio showed the following values to be most frequently encountered:

Augite Y : 1.701 } $Ca_{36}Mg_{37}Fe_{27}$.
Z : 1.724

The optic axial angle of the pigeonite is most commonly perpendicular to (010), but small values in the plane parallel to (010) were recorded. The variation is from the region of 15° in the core, to near uniaxial in the outer margins. The highest refractive indices measured were:

Pigeonite Y : 1.706) $Ca_{10}Mg_{44}Fe_{46}$.

Z : 1.733

It will be seen that the pigeonite is the most ferriferous yet encountered in the intrusion, while the augite is more ferriferous than most of the material.

...._....

MINOR CONSTITUENTS.

Titaniferous Magnetite.

The iron ore of many of the specimens achieves the importance of a major constituent, usually at the expence of the pyroxene. This is particularly true of the finer-grained specimens.

The habit is highly variable, from minute to large anhedral grains, and sprawling skeletal masses over 3 mm. in diameter in the medium-grained dolerite. In spite of the habit and the relations shown towards the earlier-formed minerals, the writer can only concur with Shannon (1924) that it is amongst the last to crystallise. Thus limbs of the skeletal growth may pierce, undeflected, both pyroxene and contiguous felspar even in the absence of any fractures in either. Usually there is a semi-opaque, dusty zone between the ore and pyroxene where this apparent replacement has occurred. All specimens show the action of residual fractions on the ore, for it has often been replaced by brown biotite. Occasional specks of pyrite may be enclosed.

The material is easily lifted by a bar magnet, but it is all but impossible to extract a pure sample not contaminated by pyroxene. Fine grinding renders the mineral incapable of being picked up by the same magnet.

The titanium content of such a sample was determined by evaporating a weighed quantity almost to dryness a few times with concentrated hydrochloric acid, filtering off the insoluble residue, and carrying out a colorimetric determination on the filtrate. The estimation showed that the mineral contains 16% of TiO_2.

For the purposes of comparison, we might note

Explanation of Plate VII.

Fig.1.

Photomicrograph of chilled fine-grained dolerite showing granular nature of the iron ore. Ordinary light (X 33).

Fig.2.

Skeletal habit of iron ore in the medium-grained dolerite. Ordinary light (X 17).

Fig.3.

Photomicrograph showing replacement, in the centre of the field, of skeletal iron ore by biotite (grey). Ordinary light (X 42).

Plate VII.

Fig.1.

Fig.2.

Fig.3.

that the titaniferous magnetites of magmatic origin in the B.I.C. contain from 16% to 19% of TiO_2, and titaniferous magnetites of the Tugela Valley from 9.2% to 19.7% of TiO_2, (see Dept. of Mines, 1940).

Micropegmatite.

At the outset, it should be pointed out that the term micropegmatite is used to define the intergrowth of quartz and alkali-felspar without implications of geometric habit. It was found that the intergrowth shows a grading from geometric perfection to the less definite myrmekitic intergrowths. The term micropegmatite is here used to include myrmekite, for it was not found possible to distinguish sharply between them.

The occurrence of micropegmatite in basaltic and tholeiitic rocks is so common as to render lengthy description unnecessary. It has been suggested (Hatch, Wells and Wells, 1949), that the interstitial moulding of micropegmatite on felspar without loss of crystal shape by the latter, is evidence that the intergrowth results simply from the crystallisation of residual magmatic liquid in the interstices between mineral grains. This interstitial and moulded habit is common in the Khale dolerite, where the intergrowth is normally radial about the felspar lath outlines, giving it a flamboyant appearance. Frequently the felspar of the intergrowth is in optical continuity with the outer mantles of the plagioclase, sometimes with a very thin selvedge of alkali-felspar without quartz between the two. Each component of the intergrowth is optically continuous for small areas, but as a whole it resembles a mosaic of small areas differing in orientation by a few degrees.

Cross-sections of these intergrowths show the quartz component as polygonal rods arranged in geometric forms. More rarely, true funic patterns can be seen. The intergrowth of the type so far described shows little modification of the crystal-shapes of the felspars on which it is moulded, and deuteric action appears to have been slight.

It seems that a second stage of intergrowth-formation was superimposed on this, for where late-stage alterations of the minerals have occurred, replacement textures become apparent. The rock as a whole loses its fresh appearance, and there is clear evidence that quartz has replaced plagioclase, even that of basic composition. All stages of replacement were observed, ranging from a deterioration of the clean-cut straight line demarcating micropegmatite from plagioclase, through loss of subhedral crystal outline, to vermiform penetration of the cores by quartz in optical continuity with that of the main intergrowth. The final stage is considered to be the the complete replacement of plagioclase by micropegmatite: this is believed to be the explanation of the peculiar characteristics of some horizons within the sheet, particularly the pegmatites. These latter rocks, as examined in thin section, are composed of large granophyric patches of quartz and alkali-felspar, showing shadowy relics of highly saussuritised plagioclase, and elongated quartz grains, with ragged ribbons of white mica up to 1 mm. in length. Portions of this rock are so distinctive under the microscope that they might have been called granophyres.

The alkali-felspar of the intergrowth is very often altered to a muddy mass of indefinite composition, rendering it almost opaque in thin section, but specimens

Explanation of Plate VIII.

Fig.1.

Moulding of micropegmatite on plagioclase, with only slight suggestion of replacement. Crossed nicols.

Fig.2.

Replacement of plagioclase by micropegmatite, with severe modification of the shape of the crystal. Crossed nicols.

Fig.3.

Replacement of plagioclase by micropegmatite, with residual patches in the micropegmatite not entirely consumed. Plagioclase outlined in ink. Ordinary light.

Plate VIII.

Fig. 1.

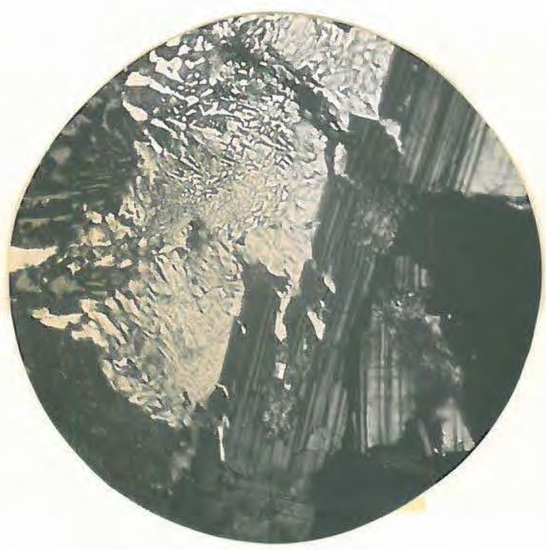


Fig. 2.

Fig. 3.

of a favourable orientation and degree of freshness showed a negative optic axial angle of 72°, as determined on the universal stage, and it is suggested it is soda-orthoclase. No consistent relation was found between the optic orientation of the quartz and that of the alkali-felspar in the cases studied.

Apatite.

It is interesting to note that that the micropegmatite is characterised by the increase, from the base upwards, in the amount of acicular, and more rarely columnar apatite. In the basal specimens apatite is virtually absent, in the heart of the intrusion it is encountered as acicular prisms and hairs up to 2 mm. long, and near the roof the micropegmatite is cross-hatched by a framework of short apatite needles. The apatite is not confined to the intergrowth, for those crystals of acicular habit penetrate both the latter and the plagioclase as well, although clearly later than it. Mountain (1937) observes, that in spite of the euhedral shapes of apatites, they may be amongst the last to crystallise.

Amphiboles.

Amphiboles are ubiquitously present in the intrusion at all levels, although they are most abundant in the dolerite pegmatites and altered specimens.

Although a small amount of the amphibole may be of primary crystallisation, it is clear that most is secondary after the pyroxene. Thus, most of the amphibole is associated with pyroxene showing signs of alteration, in stages grading from the initial mottling, through partial to complete conversion to the varieties of green amphibole. Commonly the pyroxene is complet-

completely rimmed by secondary amphibole, or may be altered on one side only, the degree of alteration bearing a direct ratio to the amount of late felsic material in the specimen, excluding those showing signs of obvious atmospheric weathering.

Two main varieties of amphibole were encountered, and probably much of the material represents a continuous grade from one to the other. The chief properties are:

Brown Hornblende

X :	Golden-Yellow	c/Z :	14°
Y :	Green-brown to deep brown	2V :	74°
Z :	Deep olive-green	Z :	1.681

Blue-green Amphibole

X :	Golden-Yellow	c/Z :	12°
Y :	Yellow-green	2V :	60°
Z :	Grass-green to blue	Z :	1.703

The two minerals above are intermediate in properties between the brown lamprobolite and blue-green hornblende described by Walker and Poldervaart (1949), except that the Z index of the brown hornblende is rather lower.

The blue-green hornblende forms outer rims to the other variety, generally as a zone widest at the termination of the c axis. The latter fact was first pointed out to the writer by Prof. Mountain, and appears to be quite a common feature. The colours become deeper towards the roof of the intrusion, with the development of deep brown and almost pure blue varieties. The distinction between the brown hornblende and biotite becomes increasingly less obvious in this aspect.

Whereas both hornblendes are associated with residual magmatic liquids, much of the pure blue variety occurs as probably primary amphibole in the mesostasis, while the brown and green-brown hornblendes tend to be marginal to the mesostasis, as well as bordering the altered pyroxenes. Together with this slight difference in associated minerals, the two show slight differences in habit. In contrast with the well-cleaved, sometimes subhedral green and brown hornblende, the blue is generally fibrous or felted, or more rarely radiating, lacking distinct cleavages, and showing streaky or aggregate polarisation.

Where the hornblende encloses granules of iron ore, or is apparently moulded on late iron ore, it is orange in colour, but grades continuously into the normal green amphibole. Inclusions of brilliantly polarising zircons with hexagonal basal sections are framed in dark brown pleochroic haloes.

Biotite.

Biotite occurs as both brown and green varieties, although the latter is present in only subordinate amount. The pleochroism is striking, from pale golden-yellow to either dense, opaque brown or rich green. The two types grade continuously from one to the other through a zone of interleaving laminae.

The biotite is commonly associated with the amphibole, as subhedral ribbons contiguous with it, or as groups of crystals of different orientations set in it. The occurrence is suggestive that much of it is an alteration-product of the iron ore, particularly in the dolerite pegmatites. Rarely an idiomorphic habit is shown in pseudo-hexagonal basal sections.

The optic properties tend to be obscured by the intense pleochroism, which renders the mineral almost opaque in certain orientations or steep angles of tilt on the universal stage. Measurements, however, show that the mineral is virtually uniaxial.

As is the case with hornblende, pleochroic haloes around small zircons are common.

Quartz.

Quartz, not intergrwon with alkali-felspar as micropegmatite, is restricted to the dolerite pegmatites. Here the habit is invariably anhedral.

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PETROLOGY.

Micrometric Data.

In view of the variations in the proportions of the different minerals, a series of micrometric analyses was carried out on selected thin sections representing a vertical section from the upper contact to a point approximately 120 feet below the contact. The purpose was to illustrate mineral changes with different distances from the contact, even in the absence of any regular trend. The measurements were carried out using the Dollar Integrating Stage, and the traverses across the thin sections were made at constant intervals, the total length being from 100-150 times the greatest possible intercept across any grain in the medium-grained rock, and over 200 times this length in the finer-grained specimens. The error in the volumetric estimation is thus probably small, and of the order of 1-2% at the most. The difficulty encountered in measuring the volumetric composition of the coarse-grained pegmatite will be appreciated by all who have attempted it, as the intercepts across any one grain might be measurable in terms of centimetres. To reduce the error in these coarse-textured rocks to less significant proportions, several slices cut at intervals of a few centimetres were measured, and the mean values taken. With the pegmatites, the micrometric analyses show the variation even at such short distances to be considerable, and great enough to be apparent in thin section to the naked eye. While the tendency to overestimate the amounts of opaque minerals is a very real danger, which becomes more significant as the mineral becomes more finely-divided and disseminated in the rock, the results, graphically expressed, indicate that this source of error is not serious.

While it is obvious that the small volume of rock in a rock section may not be representative of a larger volume of the same specimen, it is precisely that variation, or lack of accordance to a mean, which now froms the subject of discussion. Examination of Table 7 will show the variation in terms of modal composition, and, of greater interest, the manner of variation. The results are graphically expressed in Fig.6. The abscissae, plotted on an adapted scale representing distance from the upper contact, are of no importance whatever, and the points could equally well have been plotted at a constant horizontal interval: this manner of representation was adopted merely to make the information more complete.

The five sets of points plotted represent the modal percentages of the coloured ferromagnesian silicates, the plagioclase felspars, acid mesostasis and micropegmatite, iron ore, and the sum of the ore and mesostasis. The ferromagnesians comprise chiefly the pyroxenes, pigeonite and augite, with smaller amounts of amphibole and biotite, and rare chlorite. The acid mesostasis includes any intergrowth between quartz and a member of the felspar group, notably soda-orthoclase.

It will be seen that the intrusion has margins with a higher colour ratio than the main bulk of the rock, caused by a high proportion of ferromagnesian minerals and iron ore, and a correspondingly low felspar content. In this connection, it has already been noted that the felspars of the finer-grained margins are slightly more anorthite-rich, and the phenomenon is apparently an illustration of the Soret effect.

Most illuminating is a very obvious sympathetic variation between the amounts of ore and of the acid mesostasis in the non-pegmatitic rock. With but a few

Table 7.

No.	Distance from contact	Pyrox.	Felsp.	Ore	Amph.	Qtz.	Micropeg.
1.	4 inches	47.0	19.1	19.3	n.d.	n.d.	14.6
2.	12 "	38.2	20.5	20.6	5.3	n.d.	15.4
3.	23 "	47.1	28.2	15.9	n.d.	n.d.	8.8
4.	29 "	44.8	28.4	17.9	n.d.	n.d.	8.9
5.	41 "	35.3	27.8	20.0	5.0	n.d.	11.9
6.	51 "	36.5	30.3	14.7	2.8	n.d.	15.7
7.	62 "	33.0	30.9	15.7	7.2	n.d.	13.2
8.	71 "	46.5	34.3	12.0	n.d.	n.d.	7.2
9.	85 "	33.1	33.0	13.8	5.5	n.d.	14.6
10.	124 "	34.6	34.8	12.7	3.9	n.d.	14.0
11.	158 "	35.8	35.6	10.8	6.3	n.d.	11.5
12.	18 feet	37.1	35.4	9.2	3.7	n.d.	14.6
13.	28 "	36.0	35.8	11.7	1.8	n.d.	14.7
14.	39 "	41.3	37.1	8.2	4.3	n.d.	9.2
15.	68 "	36.5	39.5	10.2	3.6	n.d.	10.2
16.	102 "	34.2	40.0	8.8	5.5	n.d.	11.5

Pegmatites.							
I.		44.5	35.8	5.6	5.7	1.3	7.1
II.		34.5	32.1	15.7	4.8	1.2	11.7
III.		32.4	27.8	12.4	13.4	n.d.	14.1

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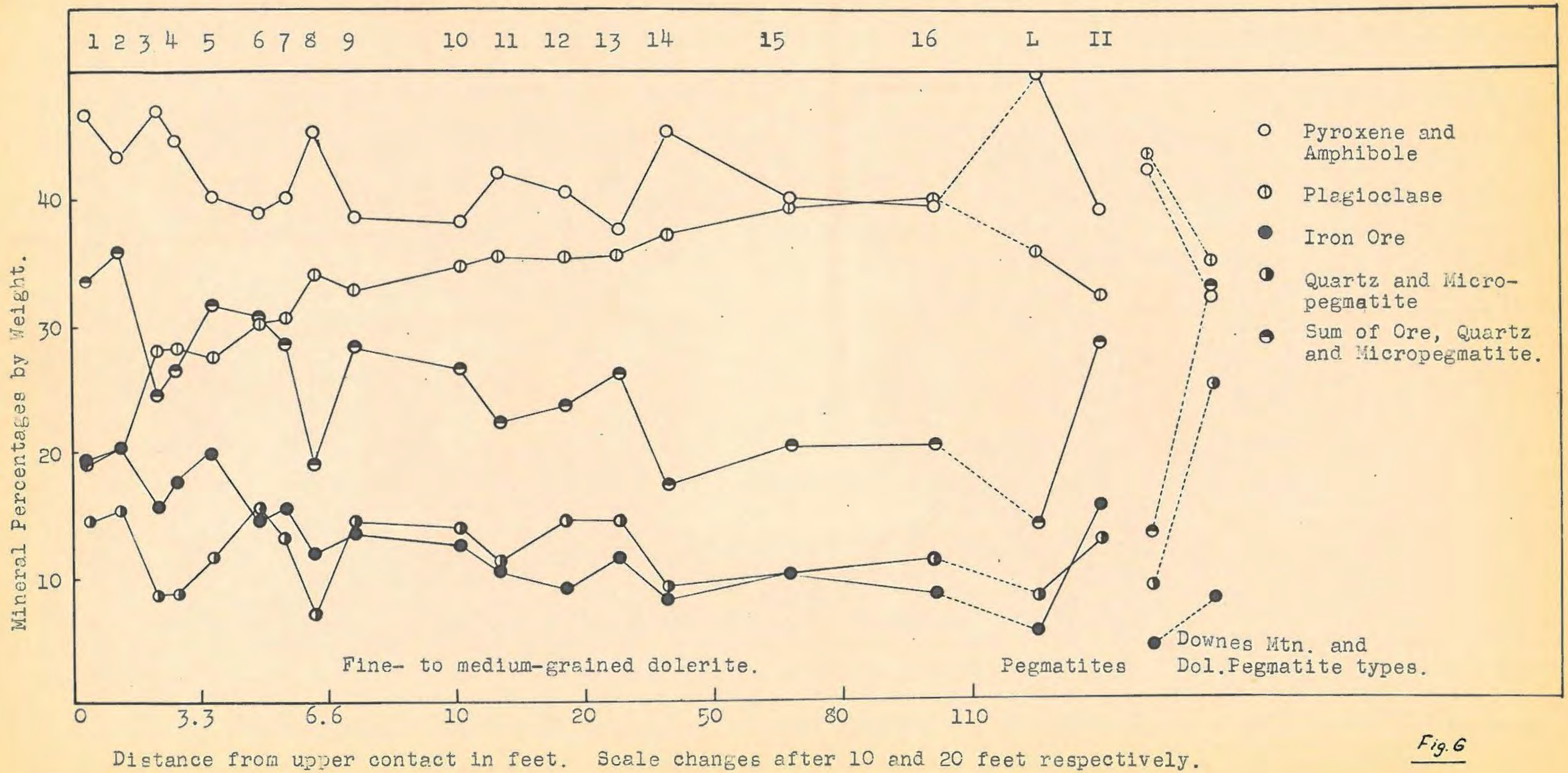


1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 L II
Pyroxene and Amphibole
Plagioclase
Iron Ore
Quartz and Micro-pegmatite
Sum of Ore, Quartz and Micropegmatite.
Mineral Percentages by Weight.
40
30
20
10
Fine- to medium-grained dolerite.
Pegmatites
Downes Mtn. and Dol.Pegmatite types.
0
3.3
6.6
10
20
50
80
110
Distance from upper contact in feet. Scale changes after 10 and 20 feet respectively.

Fig. 6

exceptions, the shapes of the two curves are similar, except that the amount of ore is apt to fluctuate more widely than that of the mesostasis.

Equally significant is the perfect antipathetic behaviour towards each other of the plotted points representing the ferromagnesians, and the sum of the micropegmatite and ore. In all cases but one, every peak or trough in the curve for ferromagnesian minerals is reflected as a mirror image by the other. Although for most of the points there is almost a plane of symmetry between the two curves, the lower one tends to exaggerate the features of the upper. The unchanging nature of this relation may be illustrated by the fact that the volumetric estimation of iron ore and acid mesostasis alone enables one to estimate the total composition of the rock, the computed values differing from those experimentally determined by only a few percent. The average modal composition of the defined Downes Mountain type, plotted on the diagram, shows the same relation.

Notwithstanding that the pegmatites show themselves to be rather more differentiated than the medium-grained dolerite,they may also exhibit the antipathetic relation between pyroxene plus amphibole on the one hand, and ore plus acid mesostasis on the other. This is illustrated by the first two modes of pegmatites in Table 7. The third mode, however, deviates markedly from this trend, and the rock contains large amounts of both ore and amphibole. It will be remembered that this type has had its orthomagmatic relations obscured by several sets of replacement processes, such as ore by biotite, and alkali-felspar of the original micropegmatite by amphibole and chlorite.

In view of the nature of the iron ore, a strongly magnetic titaniferous magnetite, it becomes clear that the underlying cause of the antipathetic relation is one concerning the oxidation state of the iron in local patches in the magma. As the modal composition of the specimens has been shown to vary within relatively short distances, measurable in terms of inches, it appears that the domain which gave rise to the specimens now examined in thin section was equally apt to change its character over short distances. The suggestion that the state of oxidation of the iron plays an important rôle in the heteromorphism of rocks of the dolerite type occurs frequently in the literature, papers of particular interest being written by Tomkeieff (1929) and Walker (1940). The last-named observes:

'The presence of volatiles has ..... entirely changed the mineral composition by preventing the iron oxide from going into chemical combination with silica as pyroxene.'

The process is illustrated by the specimens from Khale, which clearly show that a fall in the amount of pyroxene is refelected by an increase in the amount of ferric iron as titaniferous magnetite. A suggestion is made below that the first part of the quoted statement may require modification.

Furthermore, the mechanism provides, perhaps, an answer to the problem of the irregular increase in 2V angle towards the crystal margins in the pyroxenes of certain horizons, as described in the section on the mineralogy. If the decline in the amount of pyroxene is due to the inability of the ferric oxide to combine with silica, with the oxidation of the iron progressing steadily in the middle stages of crystallisation, we should then expect a relative concentration of the wollastonite minal in the outer zones of zoned crystals. T

The outer zones would thus be more diopsidic in character, and the lime could also help in the formation of anorthite and amphibole. In this connection, it is interesting to note that pectolite and prehnite are quite commonly found in dolerite pegmatites. It cannot be assumed that, to the same extent, a similar concentration of magnesia would occur, for it has been shown that the relatively magnesium-rich pyroxene, pigeonite, is essentially of early crystallisation. The remaining magnesia would also be necessary for the formation of the outer zones of the diopsidic clinopyroxene. However, at this stage, the suggestion must be regarded as tentative.

In connection with the state of oxidation of the iron, great interest attaches to the modal composition of the pegmatite, designated No.I, of Table 7. Accepting as a criterion for dolerite pegmatites that they be of particularly coarse grain, and clearly derived from the dolerite itself, this is then a pegmatite which has a higher modal percentage of ferromagnesian minerals than any of the normal medium-grained specimens, and the lowest percentage of iron ore. Clearly a specimen of this type does not support the concept that the compounds loosely classed as volatiles, can always be responsible for both coarseness of grain, and the higher oxidation state of a greater proportion of the total iron. The force of this contradiction is to some extent strengthened by the absence of a consistent relation between the modal variation, and the variation of grain-size of the felspars determined in the same rock sections.

The character of the pegmatite designated No.III of Table 7 deserves comment. The petrography of this type has been described on p.19. The modal percentages show the first observed departure from the antipathetic relation so well illustrated by all other specimens, including the pegmatites. Recalculation of the mode, by extracting the hornblende-quartz segregations, to a large extent shifts the modal values for the different minerals in such a way that the departure from the antipathetic relation is much less marked. Perhaps the most important factor in obscuring the relation is the series of mineral replacements. Thus the ore may for large areas be eliminated by reaction with residual liquid, to form biotite and possibly amphibole. The dwindling of the felspar content cannot be altogether satisfactorily explained by replacement, and the cause remains obscure. In view of the manner in which the quartz and amphibole are segregated into definite areas surrounded by a rim of reaction products, rather than disseminated throughout the rock with alkali-felspar, it is evident that the silica- and alkali-rich residuum was volumetrically more significant than in the slowly-cooled medium-grained rock. As a result the orthomagmatic relations have become obscured by the activity of these fractions.

To conclude, we might briefly consider the crystallisation-period of the iron ore. In the medium- and fine-grained rock it appears that a very small proportion had separated before the pyroxene, as evidenced by granules of angular shape enclosed in the augite. In spite of the well-defined skeletal habit, the main bulk cannot but have separated after the pyroxene. Thus in the fine-grained dolerite we find granules of iron ore in the acid mesostasis, and elsewhere the moulding of ore on pyroxene. Shannon (1924) considers the skeletal habit may be attained by the replacement of earlier minerals. The great variability in the proportion of iron ore, even at short distances, in the pegmatites rich in quartz, where the previously-noted antipathetic relation for the first time does not apply, is also indicative of the ability of the ferric oxides to move with freedom in the nearly solid rock. Thus a specimen sectioned twice, at an interval of about three inches, showed a variation from 17.3% to 4.1% of the iron ore. That the titanomagnetite has separated prior to the silica-rich fraction is clearly shown by its conversion to brown biotite.

The assumption that the composition of the medium-grained rock changes only slightly from one horizon to the next is probably substantially valid, although this is obviously not the case over too large a gap in height. Thus the antipathetic relation cited above is apparent when the distance from the contact suffers steady increase. When, however, the various components are plotted such that the pyroxenes form a continuous decreasing series, an alarming antipathetic relation appears between the plagioclase and the iron ore. The explanation is immediately apparent when it is found that this relation is enunciated by specimens less than 10 feet from the contact, and is once more an illustration of the Soret effect. Notwithstanding that the sheet is thin, and probably cooled rapidly, the existing conditions were probably ideal for this form of marginal differentiation to come into effect, as it has been shown that the magma had an abundant volatile content, which would lower its viscosity. A smooth gradation of the percentages of the various minerals has been obscured by the secondary heteromorphic effect, depending on the oxidation state of the iron. We thus come to the conclusion that the Soret effect has had a strong influence on the composition of the magma for at least eight feet from the contact, and secondly, that the manner of graphical representation of the data is valid. In short, while there may be significant changes in the chemical composition of the rock over large intervals, the present manner of representation has the effect of evenly distributing the error.

Chemical Data.

Three new analyses are presented. These include the average type of medium-grained dolerite, and two pegmatites, one of which is the pegmatite containing the high proportion of ferromagnesian minerals, and low percentage of ore. The second variety is more similar in modal composition to No.III of Table 7.

It will be seen that the medium-grained dolerite is characterised by a high proportion of iron and magnesia, and low silica, relative to the Downes Mountain type: it is, in fact, closer to dolerites of a less acid type. The mafic pegmatite is strikingly similar to this, except that the total iron increases at the expence of the alumina. The third analysis, of the more common pegmatite type, is more in keeping with the production of a slightly more silica-, iron- and alkali-rich residuum. The last-mentioned thus falls into line with the scheme of pegmatites and parent rocks in Table 9.

To the Fig. 36 in the paper 'Karroo Dolerites of the Union of South Africa' (Walker and Poldervaart,1949), has been added the plots of the analyses representing the sum of (K_2O + Na_2O), FeO, and MgO recalculated to 100. (see Fig. 7) It will be seen that the general trend is upheld, although the direction of change of the mafic pegmatite points to a more ferriferous differentiate with little change in the magnesia content.

Table 8. Chemical Analyses and Norms.

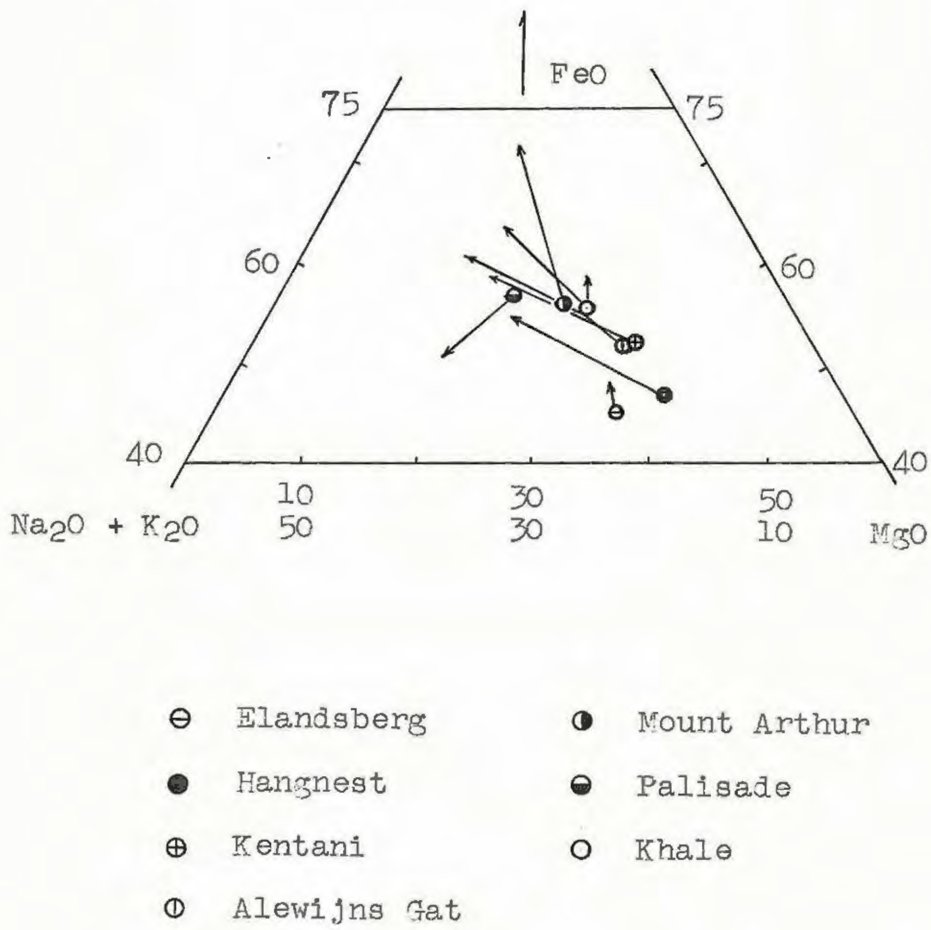
	1.	2.	3.	4.	5.
SiO_2	50.59	50.54	51.24	53.58	52.68
TiO_2	2.15	2.50	2.32	1.42	1.97
Al_2O_3	14.22	11.60	16.01	16.04	13.12
Fe_2O_3	2.66	2.33	1.42	tr.	2.14
FeO	11.10	13.31	12.94	8.63	10.62
MnO	0.10	0.13	0.18	0.26	0.23
MgO	5.35	5.86	3.24	6.02	5.13
CaO	9.38	9.26	7.53	8.74	9.44
Na_2O	2.59	2.70	3.21	2.27	2.68
K_2O	0.91	0.91	1.00	0.98	0.89
H_2O^+	0.47	0.83	0.96	1.03	0.97
H_2O^-	0.12	0.10	0.24	0.56	0.08
P_2O_5	0.29	0.27	0.17	0.22	0.22
Total	99.93	100.34	100.44	99.75	100.17

Qu.	1.48	0.62	1.50	5.5	4.5
Or.	5.56	5.56	6.12	6.1	5.6
Ab.	22.01	23.06	27.25	18.9	23.1
An.	24.19	16.68	26.13	30.6	20.6
Di. Wo.	8.58	11.37	4.41	5.0	10.6
Di. En.	4.00	5.00	1.40	2.6	4.9
Di. Fs.	4.49	6.34	3.17	2.2	5.5
Hy. En.	9.40	9.60	6.70	12.5	7.9
Hy. Of.	10.16	12.41	15.84	11.8	9.2
Il.	4.10	4.71	4.41	2.7	3.8
Mt.	3.94	3.25	2.09	-	3.0
Ap.	0.67	0.67	0.34	0.3	0.3
H_2O	0.59	0.93	1.20	1.6	1.1
Total	99.17	100.20	100.56	99.8	100.1

1. Normal medium-grained Khale dolerite. Analysis H.Eales
2. Mafic pegmatite, Khale. Analysis H.Eales
3. More typical pegmatite, Khale. Analysis D.K.Toerien and O.Winfield.
4. Downes Mtn. type. Walker and Poldervaart (1949).
5. Dolerite Pegmatite, Alewijns Gat. Walker and Poldervaart (1949).

Fig. 7.

(Taken in part from Walker and Poldervaart, 1949.)



Differentiation of dolerites and dolerite pegmatites.

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Table 9

No.	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	Na_2O	K_2O
1.	51.46	16.24	3.04	9.58	3.47	3.01	0.87
2.	52.50	18.28	1.97	7.61	2.58	3.78	1.03
3.	51.56	13.81	0.96	11.32	7.40	2.08	0.95
4.	52.94	14.80	0.16	12.00	5.42	1.98	1.50
5.	50.59	14.22	2.66	11.10	5.35	2.59	0.91
6.	51.24	16.01	1.42	12.94	3.24	3.21	1.00

1. Diabase, Palisades (Walker,1940)
2. Diabase pegmatite, Palisades (Walker,1940).

3. Diabase, Goose Creek (Shannon,1924).
4. Diabase pegmatite, Goose Creek (Shannon,1924).

5. Dolerite, Khale.
6. Dolerite pegmatite, Khale.

It is of some interest, perhaps, to compare the chemical composition of the average medium-grained dolerite with that of the mafic pegmatite in which the proportions of the plagioclase component have, by calculation, been increased by approximately one third. The composition of the plagioclase used in the calculation is An_{66}, which is the composition of the crystal cores in the medium-grained rock, and the first mineral to separate. The total iron is reckoned as FeO'.

Table 10.

No.	SiO_2	Al_2O_3	FeO'	MgO	CaO	Na_2O	K_2O
1.	50.5	11.6	15.4	5.9	9.3	2.7	0.9
2.	51.0	13.8	13.9	5.2	9.7	2.9	0.8
3.	50.6	14.2	13.5	5.4	9.4	2.6	0.9

1. Mafic pegmatite.
2. Mafic pegmatite, recalculated.
3. Medium-grained dolerite.

Although the resemblance between the recalculated values and those of the average medium-grained dolerite is far from exact, the change in the percentages of the oxides from the mafic pegmatite to the hypothetical rock is, excluding the alkalies, towards the values for the medium-grained rock: even if the values are not correct, the trend is correct. The lack of correspondence in the percentages of the soda is to be expected, as this is an element which is present in greater proportions in the pegmatitic types, and the proportion is as a result initially higher even in the mafic pegmatite. No allowance has been made for a possible small percentage of potash in the plagioclase used in the calculation.

It seems thus not impossible that the pegmatite under discussion may owe its abnormal chemical composition, in part at least, to its separation as a liquid, at an early stage, from a crystal mush in which chiefly the basic plagioclase had crystallised. This moderate form of filter-pressing would antedate the crystallisation of significant proportions of ferromagnesian minerals, leaving a residuum richer in iron, magnesia, and alkalies, but not significantly so in silica. As already suggested, the precise modal composition of the rock would then be determined principally by the state of oxidation of the iron.

The assertion that:

'all the Karroo dolerite pegmatites have a higher Fe_2O_3: FeO ratio than their parent rocks'
(Walker and Poldervaart, 1949)

does not appear to find general support out of this province. If the Khale Sheet is indeed of Karroo age, the relation also does not apply to all Karroo dolerites. Table 11 is based on analyses quoted in well-known papers, and figures for the Khale dolerite have been added.

Table 11.

Locality	Fe_2O_3	FeO	Fe_2O_3:FeO
Palisades, diabase.	3.04	9.58	.317
Palisades, diabase pegmatite.	1.97	7.61	.262
Whin Sill, Diabase.	3.50	8.85	.395
Whin Sill, diabase pegmatite.	2.42	11.35	.213
Goose Creek, diabase.	0.96	11.32	.088
Goose Creek, diabase pegmatite	0.16	12.00	.013
Khale, dolerite.	2.66	11.10	.239
Khale, dolerite pegmatite.	2.33	13.31	.175
Khale, dolerite pegmatite.	1.42	12.94	.109

The f(norm).

Use of the norm has been made to determine theoretically whether the pyroxenes or the felspars should have crystallised first in the three analysed specimens. According to Barth (1952), if the normative values of An, Ab, Di and Hy are summed, and recalculated to 100, and then the following relation is true:

$$ab' + 2\ di' + 2.3\ hy' = 123$$

then the ferromagnesian and light minerals are considered to have separated contemporaneously. If the sum, which Barth has called the f(norm), is greater or smaller than this figure, pyroxene or plagioclase, respectively, should have separated first.

The calculations showed the f(norm) to have the following values:

Normal pegmatite	:	114.1
Medium-grained rock	:	122.1
Mafic pegmatite	:	141.1

The results are more or less in accord with the textural evidence, except that the value for the medium-grained rock is rather higher than the subophitic relation would suggest. Factors other than the composition must have played a part in determining the sequence of crystallisation.

<u>Summary of Conclusions.</u>

If it is accepted, pending the accumulation of more detailed chemical data, that the chemical composition of the normal dolerite is subject to little variation from one horizon to the next, the great modal variation affords an interesting illustration of heteromorphic growth within a small intrusion. The basic factor determining the modal composition appears to be the oxidation state of the iron, whereby ferric oxides and a siliceous residuum are more abundantly present when the amount of pyroxene is relatively low. There seems to be a lack of general support for the concept that residual concentration of the volatiles will always cause the iron to be in a more highly oxidised state, although this is often the case. It is likely that the specific local composition of the group of volatiles may be an important factor, as it has been shown that coarseness of grain and a low Fe_2O_3:FeO ratio are not incompatible. The Soret effect is believed to be responsible for the higher colour ratio of the dolerite at the margins of the intrusion.

Without wishing to generalise, it is suggested that a mafic variety of coarse-grained dolerite pegmatite may be produced by the mild filter-pressing of a crystal mush in which a fair proportion of plagioclase had crystallised.

In conclusion, it is shown that the antipathetic relation between pyroxene and ore plus acid mesostasis holds also in some of the pegmatites, notwithstanding their enrichment in total iron and the alkalies. Where large amounts of amphibole and biotite are present, these are due to mineral replacements.

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MINOR VEINS

and

RESIDUAL INJECTIONS.

Minerals Associated with the Joints.

As was briefly mentioned in the discussion of the joints in the dolerite, there is a wide variety of minerals associated with these fractures, which have clearly been utilised as channelways by the late-stage mineralising solutions. In a short paper by Poldervaart (1952), a number of minerals are listed according to their degree of abundance. These are enumerated as:

Common	Less common	Rare
epidote	zeolites	hematite
chlorite	pyrite	galena
actinolite	chalcopyrite	fluorite
	titanite	

In addition to the above, the present writer has found two minerals not mentioned. No fluorite was found in any specimens.

The minerals encountered are described individually.

Epidote.

The writer hopes to do further work on the epidote at a future date, in view of its rather variable colour. The common varieties show the usual lemon-yellow and green axial colours, and occur as radiating aggregates of crystals several inches in diameter. The aggregates enclose sulphide ores of lead, copper and iron, as well as calcite and chlorite.

Chlorite.

Generally, a well-defined spherulitic habit is shown by the chlorite, which aspect, apart from the use of crossed nicols, is well brought out by the radiating cleavages, and the pleochroism. Between the crossed nicols, the spherulites extinguish partially in the form of a black cross, the arms of which are parallel to the traces of the nicols. The basal cleavages contain the slow ray. Birefringence is characteristically low, and the interference colour is anomalous berlin blue. The ill-defined interference figure indicates the mineral is optically negative, probably biaxial with 2V very small. Measurements showed:

X : 1.640
approximately.
Z : 1.645

Homogeneous cleavage fragments have a high lustre with a green sheen in certain lights. Determination, using methylene iodide diluted with xylol, gave the S.G. as 2.89.

The above properties suggest a ferriferous chlorite close to aphrosiderite.

Actinolite.

The habit of the actinolite is threefold:

(i) As a felted aggregate of lustrous, slender prisms of a dark green colour, individual prisms being up to several millimetres in length. The properties are:

X : 1.638 (yellow-green)	c/Z : 18°
Y : 1.653 (intermediate)	$2V_x$: 74°
Z : 1.665 (blue-green)	S.G. : 3.11

(ii) In the form of seams of fibrous, non-flexible crystals up to 1 cm. in length. The seams sometimes narrow to each end, but more commonly break off abruptly, thus maintaining a uniform fibre-length. In the hand-specimen, the colour is greyish-green, with a dull asbestiform sheen, and under the microscope this variety is also less strongly coloured than that described above.

X : 1.645 (faint yellow-green)
S.G. : 3.14
Z : 1.671 (light blue-green)

These seams are found either embedded in the epidote, or in dolerite partially epidotised, and themselves contain minute granules of epidote. It is interesting to note that these seams of asbestiform habit are found in the handspecimens which show slickensiding.

(iii) As a massive, granular variety, made up of a microscopic felt of minute prisms, easily cut with a knife. Again the colour is greenish-grey, but the appearance somewhat earthy. Otherwise the optic properties are similar to those of the above type. A low S.G. value of 3.05 may be ascribed to the somewhat earthy and porous nature of the aggregate.

Embedded in this variety are small, spherical aggregates of soft green chlorite, each of the shape and size of a pea, but made up of interlocking aggregates of small spherulites. These pea-shaped masses of chlorite are also found sometimes within the epidote.

Apophyllite.

This mineral occurs with, and poikilitically encloses the felt of actinolite crystals, and although the individual crystal outlines of the former are quite obvious, the volumes so enclosed may contain more of the dark than the colourless material. The habit is tetragonal prismatic, which appears superficially as cubes of side one centimetre. The crystal faces have a great number of vicinal faces, while interpenetrant growths are common. Nevertheless, goniometric measurements may be made with accuracy such as to leave no remaining doubt as to the identity. A perfect basal cleavage gives good flakes for optical examination.

The refractive index of the ordinary ray was determined with great care, in immersion media, as 1.540, and the S.G. measured as 2.36. The optic sign is indeterminate. The specimens provide an interesting demonstration of optic anomalies, even with the thinnest cleavage flakes.

Calcite.

Crystalline masses up to three inches across may be found, the most common colours being white, green and grey. The mineral is usually intergrown with epidote.

Sulphide Ores.

Pyrite, chalcopyrite and galena form small masses up to an inch in width, and several inches long, in the veins.

Titanite.

Embedded within the actinolite felt may be seen small, euhedral crystals of titanite, sufficiently well-developed to allow goniometric measurement. The colour is consistently pale brown.

Prehnite.

This mineral occurs in tiny veins with calcite and chlorite. In thin section it appears colourless, sometimes with the faintest suggestion of a brownish tint, but in handspecimens is white. The cleavage is radial about a nucleus, giving the well-known bow-tie structure, perhaps better observed between crossed nicols.

X : 1.636

Y : 1.640 2V variable (36°).

Z : 1.657

Small granules with a S.G. of 2.86 were also picked out of the actinolite felt.

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Residual Injections.

In the form of thin veins, generally in the upper parts of the intrusion, late-stage residual injections may be studied in the field. A typical vein of this type can be seen to start some thirty feet below the upper contact as a light coloured streak on the bare rock surface, swelling upwards to a maximum of two inches in width, and dying out once more within a few feet of the upper contact.

The chief characteristics, discernable without resort to laboratory technique, are:

(i) The sinuous outcrop, and lack of consistent dip and strike.

(ii) The highly variable colour index, varying between the limits of leucocratic and hypermelanic types.

(iii) While in the main veinlike in appearance, clots and swellings of anchimonomineralic material are present. These clots may be of either coarsely crystalline amphibole or albite.

(iv) Most commonly, decomposition by weathering is well advanced, altering the rock to a friable powder, even where it is in contact with the fresh host rock.

The handspecimens of the leucocratic variety are creamy-white in colour, flecked with dark amphibole and green epidote. Individual crystals reach lengths of 5 mm. on cleavage faces, and the relatively high degree of idiomorphism is reflected by the specimens breaking so as to leave cavities of geometric shape on the broken surface. The hypermelanic clots are composed of well-crystallised hornblende prisms up to 2 cms. in length. There are intermediate varieties represented by speckled rocks.

Microscopic Evidence.

It is here most convenient to describe the three varieties separately, each in turn.

Leucocratic Variety.

This consists almost exclusively of highly sodic plagioclase, determined as An_3, highly charged with minute inclusions, rendering them on occasion almost opaque. The composition planes of the twins, and crystal margins are clearly outlined by their being relatively free from foreign matter. Some of the plagioclase shows a curious speckled extinction, which appears to be due to a combination of intergrowth and twinning structures.

Quartz is present as an anhedral interstitial filling, and the manner in which these anhedra are optically continuous although not joined in the plane of the slide, shows it to be amongst the last to crystallise. These crystals show no signs of strain. Granular and cellular epidote, with ragged laths of hornblende, may be found scattered throughout the rock. Local patches may contain striking columns of poorly-cleaved prehnite, subpoikilitically enclosing the plagioclase. The properties of the prehnite are:

X : 1.617	$2V_Z$: 60°
Y : 1.624	c/Z : 90°.
Z : 1.643	

This leucocratic variety forms the main bulk of the vein material.

Hypermelanic Variety.

Slides including both the segregation and host rock of the vein margins show a striking degree of idiomorphism of the hornblende prisms, oriented as a weakly-developed comb-structure with regard to the vein margins.

The contiguous country rock is highly chloritised and saussuritised.

In addition to their being almost universally twinned on the (100) plane, the optic properties of the hornblende are:

X : 1.672 (Pale golden-yellow)
Y : (Deep brown) c/Z : 17°
Z : 1.690 (Brown)

Of lesser importance are a number of interstitial minerals, chiefly ill-crystallised and fibrous blue-green amphibole of high but streaky birefringence. Concentrically-zoned spherulites of chlorite are pleochroic from pale yellow to bright green, with birefringence in the core approaching sensitive tint, but falling off to the more common low values in the outer rims. Secondary after the brown hornblende is a variety of an intense red colour, the lightest axial colour being amber. The latter occurs as narrow zones between rare quartz anhedra and hornblende, in the interstices between hornblendes, or along cleavages.

A certain amount of shearing, probably related to the contraction during cooling, has resulted in the development of close-spaced fractures parallel to the vein margins, which have provided channelways for hydrothermal solutions. These solutions, in passing through the brown hornblende, have metasomatised them to an intense blue-green variety for a total width somewhat less than one millimetre.

Speckled Variety.

These specimens contain plagioclase and amphibole in approximately equal proportions. The latter, in contrast to that of the rock described above, takes the form of ragged aggregates showing a complete absence of crystal faces. Although much weathered and oxidised, the amphibole can be seen to be pleochroic from brown to deep green. The plagioclase is unchanged in composition, but sphene, both as euhedral crystals and cellular anhedra, is present as a critical mineral, while both quartz and prehnite are absent. Epidote appears as before.

Possibly of significance is the fact that within a zone of some 3 mms. width, bordering this speckled rock, the plagioclase laths of the leucocratic variety are concpicuously parallel, thus showing a crude flow structure. As this structure is not characteristic of the vein as a whole, it would appear that the speckled variety was the first to achieve a relatively solid state, and the subsequent contractions of the intrusion oriented the crystal laths in the mush which was to solidify as the leucocratic rock. Assuming that the speckled rock merely formed a local constriction in the vein, the absence of flow structures parallel to the vein margins in other parts of the vein could be explained.

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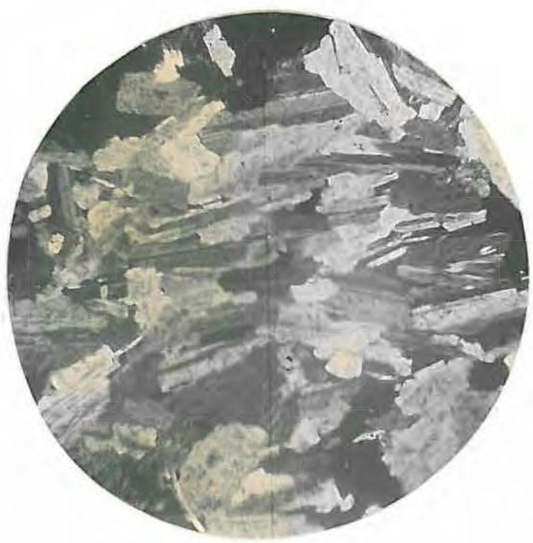
Plate IX.



Residual injection of albite, clearly showing the parallel alignment of crystals. Crossed nicols (approx. X 30).

Hydrothermal Veinlets in the Granite.

Above the upper contact, the coarse-grained granite country rock has innumerable tiny veinlets or stringers of dark material which have emanated from the dolerite. Even at a height of some forty feet above the dolerite, they may be found in profusion, although they find their greatest frequency in the horizon immediately above the contact.

In the handspecimens, the veinlets resemble black pencil lines in the red country rock, and have a dull appearance. Rarely are they thicker than 2 mms. in local swellings, and are generally less than 1 mm. What makes them worthy of note is their astonishing persistence for many feet in spite of their extreme thinness. In the bed of the Notwani River, the smoothly rounded slabs of granite take on a reticulate appearance where the veinlets intersect in a pattern similar to diamond-mesh fencing.

In polished surfaces of the granite, the veins appear to cut through all of the minerals, except where there are exceptionally large quartz grains. In this case, the veins are continuous on both sides of the quartz grains.

In thin section, the veins are seen to be composed chiefly of three minerals. There is no suggestion of straight edges bounding the margins of the veins, but a highly irregular and ragged surface. Isolated clots and nests up to 2 mms. in diameter are scattered about in the rock, and these may be connected to the veinlets only by channelways of small, fritted quartz granules. The whole picture suggests utilisation of fracture-planes in the granite for the movement of active fluids emanating from the dolerite.

The veins are mineralogically composed of fibrous, pale green chlorite, showing anomalous mauve interference colours. The pleochroism is from colourless, to pale green parallel to the cleavage, and the extinction is parallel. Set in this are minute granules of partially replaced magnetite. Where chlorite is present in only subordinate amounts, magnetite becomes the chief mineral, taking on a cellular habit. A white coating on the magnetite indicates that it contains significant amounts of titanium. A variety of amphibole with small extinction angle, and pleochroism from pale yellow-green, to reddish-brown parallel to the slow ray, is present as grains of irregular shape. An unidentified uniaxial positive mineral with high relief, ranging from colourless to an irregular, blotchy red colour, occurs as scattered crystals in one small magnetite-chlorite nest.

It is considered that these veinlets have a hydrothermal origin, residual fluids having made use of microscopic fractures in the granite, in their upward percolation. In view of their ragged margins, and the embayments in the minerals of the host rock, it is likely that a certain amount of replacement and reaction has occurred.

This opinion can to some extent be substantiated by an examination of the thin slices of the chilled dolerite margin. After careful selection of a pair of handspecimens of this rock in the field, sections were cut which matched the emergence point of some of the veinlets. The thin sections in turn show, quite clearly, a thin streak, 2-3 mms. wide, in which the fresh pyroxene-plagioclase-ore rock has been altered to one consisting of amphibole, quartz and ore. The presence of areas of quartz 0.8 mms. long, is alone proof of the penetration of the chilled contact rock by late-stage fluids. Equally suggestive is the fact that, of the two varieties of amphibole, with olive-green and red-brown Z axial colours respectively, the latter variety forms about 30% of the total.

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Explanation of Plate X.

Fig.1.

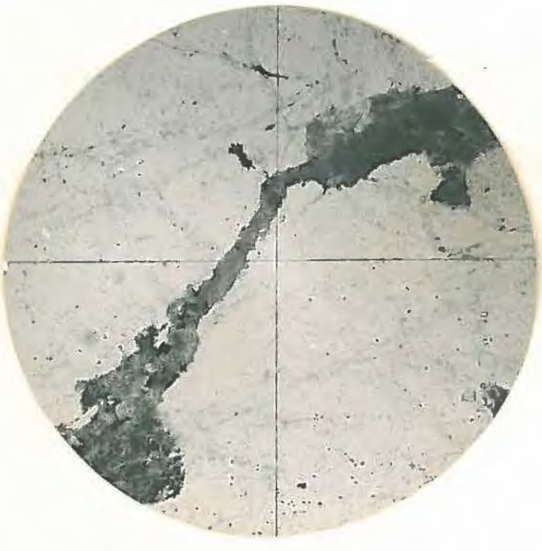
Pattern of hydrothermal veinlets emanating from the dolerite, as seen in the weathered surface of granite exposed in the river bed.

Figs.2 and 3.

Photomicrographs of chlorite veinlets cutting through quartz grains in the granite. Ordinary light (X 42).

Plate X.

Fig. 1.



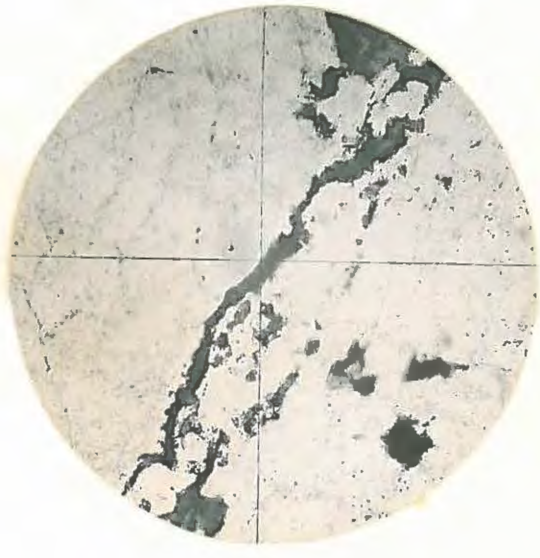


Fig. 2.

Fig. 3.

Veins of Mobilised Granite.

Near the upper contacts, where the dolerite crops out in the North Hill, and in the plain, near the river, there are exposed in the younger intrusion a few thin veins, which appear to owe their origin to the rheomorphism of the granite. Poldervaart (1952) asserts that no rheomorphic veins have been found associated with dolerite in the south-eastern Bechuanaland Protectorate, but it should be mentioned here that the upper parts of the Khale intrusions are usually well exposed, whereas the above writer notes that most of the intrusions he has studied in this area have the upper contacts poorly exposed.

These veins are in all cases small, not exceeding a maximum width of two and a half inches, and of vertical attitude with short vertical extension. In all of the sparsely outcropping veins, they were found to die out before penetrating the dolerite by more than 30 feet. The veins appear to be related to the mechanism of contraction, for they are parallel to the joints developed there. Xenoliths are even more restricted to specific horizons, not being found more than six feet from the upper contact. Thus, were it not for the favourable exposure of the upper contact, it might have been accepted that no rheomorphism of the granite had taken place.

Unfortunately, in no case was it possible to trace the veins in an unbroken sequence from the dolerite into the granite, due to a purely fortuitous presence of rubble overlying the contacts where they are exposed. However, the restriction of the veins to the vicinity of the upper contact, their vertical attitude and the manner in which they die out vertically downwards, and their appearance, both megascopic and microscopic, strongly suggest mobilisation is responsible for their presence. In appearance they are quite different from the late-stage injections of residual fractions. The rheomorphic veins and the veins of residual fractions may occur side by side.

The veins were studied in the field in two localities, firstly near the river, where the upper contact is exposed beneath low granite hummocks, and in the vicinity of the ballast quarry. The weathered surfaces are of a reddish-brown colour, and their higher resistivity to weathering is reflected in their forming ridges slightly raised above the weathered surface of the dolerite.

It is interesting to note the age relationships of the veins indicated by the field evidence. They cut the numerous horizontal schlieren of dolerite pegmatite and are in turn older than the chlorite veinlets which figure so prominently in the intrusion, for the latter are cut , or are deflected by the mobilised material. The fact that there has been no mechanical mixing of the rocks, or tendency of the veins to separate into a string of xenoliths, suggests that the dolerite was almost completely solid before the plastic material was drawn into it. The act of mobilisation thus probably took place at the closing of the orthomagmatic stage, and prior to the hydrothermal stage.

Petrography.

Handspecimens are characterised primarily by their being of a pale grey colour ; others may show a streakiness parallel to the sides, in the alternation of light and darker bands. Progressive stages of change are shown in handspecimens of the vein rock with increasing distance from the contact, the advanced stages bearing little resemblance to the parent granite. Thus is first produced a blastoporphyritic aggregate of quartz and alkali-felspar with subordinate ferromagnesian minerals, which changes to a pasty-looking rock with streaks of light and dark material. In the latter rock, the pale streaks contain rare insets of quartz and alkali-felspar in a pasty groundmass almost without dark minerals, while the dark streaks are found consistently marginal to the host dolerite and less frequently as discontinuous streaks in the core of the vein. The dark streaks are more or less equigranular. Locally this rock may show patches a few centimetres across which are intermediate in colour, or coarser in grain than the variants outlined above. Where the veins have come in contact with mineralising solutions, galena, zeolites and sphene have been introduced, along fractures in the nature of joints.

Microscopic Evidence.

Under the microscope, the veins show an interesting gradation of textures and mineral composition. In the absence of specimens of the veins at the immediate contacts between dolerite and granite, the specimens closest to the granite are first studied.

Porphyroclastic Rock.

Such specimens show an inequigranular rock with insets of quartz and alkali-felspar up to a centimetre in diameter, set in a fine-textured mosaic of chiefly quartz and alkali-felspar, with subordinate ragged laths of amphibole. The quartz insets contain rows of inclusions, and tend to be repeatedly fractured, such fractures lying more or less parallel within the slide as a whole. The crystal edges are scalloped and partially recrystallised to a mosaic with alkali-felspar, or penetrated by stringers of the same material, until the quartz crystals may eventually become merely isolated patches all in optical continuity. Near extinction, marked strain is apparent, the extinction shadows forming bow-tie shaped shadows about inclusions. The quartz of the groundmass consists of unstrained equidimensional grains, and the almost universal fall in birefringence from core to margins indicates that their shapes approximate to the spherical.

The felspar insets at first sight resemble perthite, but favourable orientation achieved on the universal stage shows them to be twinned with exceedingly fine, rather irregular, albite lamellae. As with the quartz, they are rendered septate by stringers of the groundmass. The crystals are completely anhedral, with numerous indentations by the material of the groundmass. The composition, as given by the Fedorov Method, is An_5. The composition of the felspar of the groundmass is the same, and although much of it is untwinned, shows a constant 2V angle of 76°-80°.

It is surprising that potash felspar is all but absent, for protracted search showed only a small proportion indeed of untwinned felspar with a negative optic axial angle in the region of 70°, with refractive indices less than that of quartz. Such rare anhedra of potash felspar in thin section appear to be mere remnants which escaped the process of replacement by nearly pure albite. All felspars are densely clouded with inclusions of rod-like and irregular shape, which are probably amphibole.

Amphibole of variable properties is present as ragged laths showing streaky pleochroism and birefringence, due to partial chloritisation along the cleavages. The pleochroism is :

X : Pale yellow

Y : Greeny-brown

Z : Blue-green

Associated with this is a rare mineral of striking pleochroism , which is probably an oxidised variety of the more common blue-green amphibole. From these rare crystals the following properties were obtained:

X : Pale yellow

Y : Golden brown to reddish $2V_x$: 66°

Z : Slightly lighter than Y

The mineral shows at least three good cleavages, arranged more in the nature of segments than as intersecting sets, giving a distorted pseudo-hexagonal shape, and is strongly zoned from a reddish-brown core, to tints closer to those of the blue-green hornblende in the outer rims. Birefringence grades up to third order in some sections, and extinction is parallel to one set of cleavages, and up to 36° from another equally well-defined set. The mineral is probably an amphibole close to kataphorite.

Tiny crystals of clear green hornblende are associated with spherulites of pleochroic chlorite showing a well-defined extinction cross between crossed nicols. The chlorite shows remarkable zoning, concentric about the centre of the spherulites, in the presence of a curved or circular zone of colourless chlorite in striking contrast to the normal green colour, but having also parallel extinction. Basal sections are non-pleochroic and apparently isotropic, whereas the sections showing sharp cleavages have a birefringence of about .004.

Streaked Rocks.

The specimens with a streaked appearance, under the microscope, show this to be due to the alternation of bands of amphibole-rich and amphibole-poor composition. Marginal to the dolerite is always developed a zone about 10 mms. wide, where hornblende is present in a proportion variable around 50%, the rest of the rock consisting of felspar too highly altered to allow of determination, but showing albite twinning, and interstitial quartz. Acicular apatite penetrates the quartz, felspar and hornblende in an irregular network. The hornblende adjacent to the dolerite shows euhedral basal sections, and is rather deeper in colour than those in the core of the vein, approaching deep green-brown rather than bluish-green. This zone grades into another of similar character, but in which the hornblende is bluer in colour, and arranged as sets of parallel laths at low angles to the vein margins.

The light coloured streaks of the handspecimens are shown to be a granophyric intergrowth of albite and quartz, the former with a composition similar to that of the albite of the higher porphyroclastic specimens. The shape of the quartz component in the intergrowth is not polygonal as it commonly is in micropegmatite, but round, oval or irregular in cross section. Both components are optically continuous over small areas, and polysynthetic twinning of the albite component is shown in favourably oriented sections.

Dark streaks in the core of the vein are similar to those marginal to the dolerite, except that the grain is coarser and the amphiboles ragged, arranged parallel to the sides of the vein. The colour of the amphibole tends rather towards a streaky sea-blue, than the greeny-brown of the marginal variety. Granular sphene and altered ilmenite in intimate association are plentifully scattered about.

Some thin sections show the obvious effect of movement of the rock subsequent to the growth of the granophyric structures, for these have been rolled to a fine-grained aggregate of rounded quartz grains and albite which may again enclose lenticular streaks of coarser or finer grain. A second attempted recrystallisation of this fine-grained rock is shown by a few scattered nuclei about which granophyric intergrowths have started to form.

Thin sections of the veins taken from the lowest horizons, before they apparently lose their separate identity, show mineralisation by hydrothermal solutions by the presence of stringers containing calcite, galena and sphene. The calcite has very clearly replaced the quartz crystals in many places , as minute stringers with convex margins. It is interesting to note that some of the clouded albite has now been rimmed by an overgrowth of perfectly clear albite in optical continuity.

It is considered that the textures exhibited are the results of three processes:

(i) Replacement.

(ii) Recrystallisation.

(iii) Crushing by movement.

The attack on pre-existing minerals by albitic plagioclase is perhaps one of the most striking features of the specimens. In the higher blastoporphyritic rocks, the insets of quartz show vigorous scalloping of their margins, replacement by stringers of albite, and the replacement of their cores by twinned albite, where fractures within the grains have allowed easy access of the replacing medium. In plane light the material immediately surrounding some of the quartz insets is made of clouded felspar without the clear windows of quartz as in the remainder of the groundmass; this rim, between crossed nicols is seen to be made up of an aggregate of rather small twinned crystals of albite.

The absence of potash felspar, with the rarest exceptions of a few residual grains transected by twinned albite must certainly be ascribed to the same metasomatic replacement.

It is considered that much of the amphibole of the core of the vein was introduced late in the sequence of events. The reasons for this are the ragged and skeletal shapes of many of the hornblendes in the core, the transecting of the vein by veinlets of blue-green hornblende and sphene, and a strong suggestion that imperfectly developed 'granophyric' intergrowths between quartz and hornblende are due to the replacement of the albite by the amphibole. There is no evidence of the hornblende preceding the quartz, apart from the marginal amphibole zone, for the former is invariably moulded on the quartz grains where they are in contact. In this connection it is interesting to note that similar intergrowths between quartz and green amphibole were described in the dolerite pegmatite by the present writer.

Whereas much of the albite-quartz intergrowth is no doubt due to replacement in the upper rocks, the lower streaked rocks have probably had their fabric modified to a greater or lesser extent by recrystallisation. The evidence for this lies in the streakiness of the rock, and the developmentsof intergrowths approaching more nearly the patterns seen in micropegmatite. In the leucocratic streaks, the grain-size is considerably increased relative to that of the enclosing material, which also suggests the same process of recrystallisation.

In the rocks showing the breaking down of the granophyric intergrowths to an aggregate of rounded quartz grains set in an alkali-felspar matrix, with lenticular streaks of coarser grain-size, it has already been indicated that incipient recrystallisation about scattered nuclei has produced suggestions of granophyric patches of a second generation.

Conclusions.

While it is fully appreciated that there is a real danger of mistaking injections of late-stage material for syntectic or rheomorphic veins, there is reason to believe that the veins described in this chapter are of mobilised granite which has been changed in character by a process of metasomatism. Although there are certainly points of similarity between undoubted late-stage residual injections and the veins in question, the appearance in the field and under the microscope, leads the writer to believe at the present time that the two have separate origins.

The metasomatic replacement is, perhaps, to be expected, for it has been shown by Walker and Poldervaart (1949) that albitisation is a feature most commonly associated with rheomorphism. The high volatile content of the intrusion would contribute to the processes which effected the mobilisation.

The evidence presented above serves to indicate that there is field for further research, particularly concerning the chemical aspects, into the possibility that rheomorphic phenomena might, in this area, be more common than is suspected.

Explanation of Plate XI.

Fig.1.

Vein of mobilised granite in dolerite. Outcrop near the river.

Fig.2.

Mosaic of quartz and alkali-felspar with subordinate ferromagnesian minerals, forming part of the vein. Crossed nicols (approx. X 25).

Fig.3.

Pale streak composed of a granophyric intergrowth of quartz and alkali-felspar, practically without ferromagnesian minerals. In the hand-specimen the streak is about 5 mm. wide. Crossed nicols (Approx. X 25).

Fig.4.

Concentric zoning about several nuclei of chlorite spherulites in the vein. Ordinary light (X 37).

Plate XI.

Fig.1.

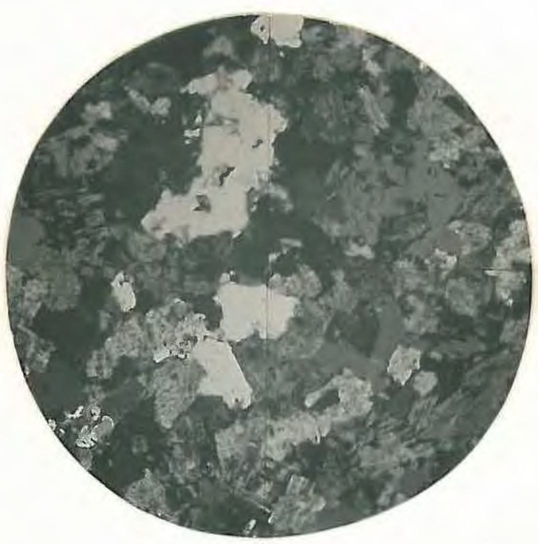


Fig.2.

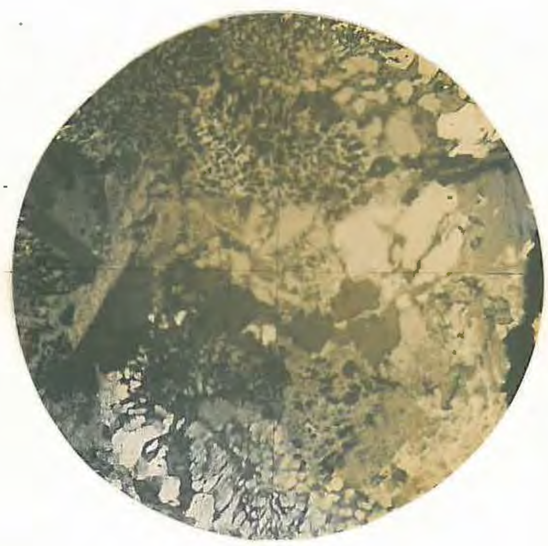


Fig.3.

Fig.4.

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