STUDIES IN METAMORPHISM AND ASSIMILATION IN THE WELLINGTON DISTRICT, N.S.W.

I. HYBRIDISATION IN THE WUULUMAN CREEK INTRUSION.*

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(With seven text-figures.)

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1. INTRODUCTION AND PREVIOUS RECORDS.

Wellington is situated on the main western railway 255 miles from Sydney, at the junction of the Bell and Macquarie Rivers. The Wuuluman Creek intrusion crops out 10 1/2 miles to the east of the town in the parish of Wuuluman, and is crossed by the Wuuluman road 1 1/2 miles

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east of Poggy Creek. The intrusion, which measures $1\frac{3}{4} \times \frac{1}{3}$ miles, invades folded Silurian sediments, and consists of an earlier dolerite and a later keratophyre, which has injected and hybridised the dolerite; this suggests that they were consanguineous. The north-west part of the igneous mass and the adjacent sediments have suffered shearing due to movement along a fault-plane. The Wuuluman granite, which crops out about half a mile to the north of this intrusion, does not exhibit shearing, and appears from the field evidence to be later than the fault. It is most likely, therefore, that the Wuuluman Creek intrusion is pre-granite.

No petrological work has been published on the Wuuluman Creek intrusion, but Matheson (1930) and L. J. Jones (1935) have mapped the area, and the latter has kindly allowed the present writer to examine some of the microslides belonging to the N.S. Wales Geological Survey. During 1938 Miss M. J. Colditz and the writer carried out further geological mapping, and it is hoped that the map will be used in connection with some later work.

2. NATURE OF THE INTRUSION.

The main part of the intrusion has an east-west elongation. Small outcrops of dolerite are found at distances varying from 10 to 30 chains to the south-west, north, and east. To the south the Wuuluman Hills, situated just south of the Wuuluman road, may cover other masses. These outcrops would appear to be tongues of dolerite from the main mass which have penetrated the surrounding sediments. It would seem that the intrusion is a small boss rather than a dyke as suggested by the shape of the main outcrop.

The keratophyre has a rather sporadic distribution (see map). On the eastern side of the intrusion in Por. 69, Par. Wuuluman, a fairly large mass is exposed on the top of the hill, and several smaller ones occur to the east, while in the western part of the area smaller rather dyke-like outcrops and veins invade the hybrids. Only the largest outcrops of keratophyre are shown on the map. Surrounding the keratophyre intrusion are spotted hybrids, indicating that they were produced by the injection of the keratophyre into the dolerite, while the occurrence of wide areas of spotted hybrids within the dolerite suggests that the keratophyre is not far below the present surface. Since the dolerites crop out on the hill in the western part
of the intrusion, and patches of spotted hybrids are found within the keratophyre to the east, it would seem that the younger intrusion was enclosed within the dolerites and did not penetrate to the surrounding sediments.

3. Petrography.

(I) The Parent Rocks.

With regard to the nature of the original rocks Uttle can be said with certainty, as all samples of the basic type are hybridised or partially metamorphosed, and the acid phase has been considerably modified by the incorporation of disintegrated xenoliths, so that it is unlikely that any unaffected material will be revealed.

(a) The Altered Dolerites.

The altered dolerites show slight variation both in mineral composition and texture. The greater part of the mass has an ophitic to slightly poikilitic texture, due to the development of masses of augite and possibly of some hornblende, but in places these tend to develop their own crystal form. The ophitic fabric seems to be an original structure. Zoning and twinning were fairly common in the augite.

In the more eastern portion of the intrusion elongated masses (10 mm. x 0.5 mm.) of fibrous uralite, or criss-cross flakes of biotite, associated with abundant iron ore, indicate the presence of long crystals of hornblende in the original rock. In this rock the felspar crystals are larger and better formed. This type, however, is not widely distributed and probably represents a slightly more acid differentiate of the doleritic magma, and could best be called a hornblende-bearing dolerite.

The plagioclase is nowhere unaltered, so that the original composition cannot be determined, but the abundance of epidote granules would indicate that it was a fairly basic type. The fairly frequent arrangement of epidote granules into zones is probably due, at least in part, to original zoning in the felspar.

Apatite is present in varying degrees as well-formed prisms up to 0.75 mm. in length, exceptionally reaching 6 mm. It is mostly pale bluish to purplish grey and contains many minute iron ore inclusions, generally arranged parallel to the elongation, but sometimes unoriented. Another peculiarity of this apatite is that it...
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Apatite is present in varying degrees as well-formed prisms up to 0.75 mm. in length, exceptionally reaching 5 mm. It is mostly pale bluish to purplish grey and contains many minute iron ore inclusions, generally arranged parallel to the elongation, but sometimes unoriented. Another peculiarity of this apatite is that it
is hollow, giving the cellular structure often shown by tourmaline, and the central portion is now largely filled with green biotite. Ilmenite in grains up to 1.5 mm. long and often showing skeleton structure is very abundant. This rock has been called an altered dolerite for the following reasons: (i) There are indications of an original ophitic fabric. (ii) In the sheared zone there is a dynamically altered type which contains albite but no quartz (see p. 181). The absence of quartz would suggest that the rock has not been hybridised, so that the anorthite-molecule must have been removed previously. It seems probable therefore that the rock had been deuterically altered before the injection of the keratophyre magma. (iii) The analysed rock agrees fairly closely with other altered dolerites (see Table II, columns I and VI).

(b) The Keratophyres and Quartz Keratophyres.

These types are fine- to medium-grained hypidiomorphic granular rocks. All specimens have been considerably hybridised, but much of the assimilation has been mechanical, so the nature of the original rock may be surmised. The chief constituents are idiomorphic albite crystals (Ab$_{91}$An$_{9}$ to Ab$_{99}$An$_{1}$), orthoclase, quartz, and possibly some biotite. The variation in the composition of the plagioclase may in part be due to assimilation. Quartz fills interstices or is associated with albite or orthoclase in micrographic intergrowth. Dust-like inclusions, sometimes showing parallel arrangements, are fairly common in the quartz. Deuterie alteration of the albite by potash-bearing solutions fairly commonly results in the formation of microperthite.

Little can be said regarding the original ferromagnesian minerals, as the rock contains large quantities of criss-cross flakes of biotite, grains of ilmenite, magnetite, a little pyrite, and granules of epidote, most of which have evidently been derived from the disintegration of dolerite xenoliths. However, it is probable that the pyrite and some of the magnetite belong to the keratophyre, as they are generally absent from the dolerites.

Apatite is not abundant in the main body of the mass, but it is very well developed in association with keratophyre veins found penetrating the spotted hybrids. It is usually formed along the edge of the vein or within the adjacent rock with the elongation of the crystals parallel to the length of the vein (see Fig. 6 A). The prisms are small,
colourless, and show no cellular structure and so may be easily distinguished from the apatite of the dolerite.

On account of its texture and chemical composition this rock may be called a keratophyre (see Table II, column V). Quartz was not abundant in the analysed rock, but there are others which may be called quartz-keratophyres.

(ii) Hybrid Rocks.

The hybrid rocks are formed both by the incorporation and mechanical disintegration of fragments of dolerite in the invading keratophyre magma, and by the percolation of these solutions through the rocks of the earlier intrusion. Naturally there is a region where it is difficult to decide whether the hybrid belongs to the first or to the second group, and it is here that most of the rocks which have a peculiar spotted appearance belong.

(a) Hybridised Dolerites.

In the normal dolerite, which is the most abundantly developed type, the progressive mineralogical changes produced by the introduction of solutions from the keratophyre are most clearly shown.

The augite is changed completely to uralite. It is a pale green hornblende, \( X = \) yellow green, \( Y = \) deeper yellow green, \( Z = \) blue green. \( X < Y < Z, \) optically negative, with positive elongation, \( Z / c = 31^\circ. \) The original polysynthetic twinning of the augite is very well preserved, often being oblique to the elongation of the fibrous crystals. Included felspar laths are often completely replaced, and sometimes changes in the direction of growth of the fibres are produced due to the arrangement of cleavage cracks in the felspar.

The originally basic felspar is completely albitioned and the anorthite molecule has apparently been removed in solution. The composition now is \( Ab_{96}An_5 \) to \( Ab_{92}An_8. \) Clouding (Maegregor, 1931) is sometimes found in the plagioclase. With slightly more impregnation rims of clear, often untwinned, albite are visible around the plagioclase of the dolerite. Very often at about this time clinzoisite and epidote are developed in the original plagioclase. The arrangement of these minerals is somewhat variable. In many cases they form tiny granules showing a greater concentration towards the edge of the laths; in others they are found throughout the mineral, giving it a greyish appearance; yet others show tiny granules around the edge, with prisms up to 0.1 mm.
in length towards the centre. These are often found in association with sericite, which has a sporadic distribution throughout the hybrids and is in places developed to the exclusion of albite in the altered felspars.

At the stage when rims of acid felspar are formed round the originally basic felspar, small needle-like crystals and fibrous masses of green hornblende crystallise from the surrounding hybrid magma. Later, with the introduction of solutions containing some potash also, this hornblende and the uralite become unstable and are replaced by masses of criss-cross flakes of biotite. It is greenish to brown in colour and develops first between the fibrous crystals, and often greenish brown patches enclosed by deep blue-green material can be seen in the surrounding uralite. This generally precedes the formation of the biotite. Around the edges of the uralitic masses, and sometimes as an outer zone to the hornblende which has crystallised from the hybrid magma, a deeper green to bright blue-green amphibole is developed. This is most likely a more actinolitic variety. With greater impregnation all the hornblende is gradually replaced by flakes of biotite, but the change is complete only in the most acid spotted hybrids.

During these changes tiny needles of hornblende, or biotite flakes, are formed in places in the felspar, and they are probably produced from small quantities of included chlorite. There is also a gradual change in the ilmenite, narrow rims develop round the larger grains, gradually replacing the mineral, and the skeleton masses are now represented by compact masses or minute crystals of brown sphene.

These alterations in the dolerite are accompanied by a gradual increase in the quantity of keratophyre solution introduced. First, rims of albitic plagioclase develop round individual felspar laths, penetrating along cleavages or surrounding groups of laths, while close by no rims are found. Generally they tend to preserve the shape of the surrounded mineral, and where interstices are left they are filled with quartz, which may be partially intergrown with the felspar. With increasing injection "pools" (Nockolds, 1938) of hybrid keratophyre magma are produced, due to the further separation of the plagioclase laths. These are roughly rounded patches of albite and quartz showing varying degrees of intergrowth and dispersed biotite flakes, surrounded by the lath-shaped plagioclase crystals of the

An analysis of a hybridised dolerite is given in Table II, column II.
dolerite (Fig. 2 A). The quartz may have regular boundaries or may merge into micrographic intergrowth with plagioclase and show no signs of strain; but in other places it is strained and granulated, and material containing biotite and epidote, with or without albite, is found between the grains. Undulose extinction may be the result of strain due to shearing, but the other phenomena seem to indicate that some of the quartz which crystallised at the time when the albite rims were formed has been broken up by a later injection of the hybridised keratophyre magma. Sometimes considerable corrosion of the original basic felspars has taken place and they are now reduced to irregular masses of epidote granules, with associated albite or sericite, surrounded by hybrid keratophyre material or flakes of biotite. The presence of microperthite in some of the “pools” and in the rims surrounding the felspar cores indicates a partial replacement of albite by orthoclase, and suggests a sporadic concentration of potash towards the end of crystallisation. This is also shown in the keratophyre itself (see p. 165).

Towards the eastern end of the intrusive mass the injection of hybrid keratophyre magma has not been so peaceful, and disintegration of the replaced augite crystals with marked strewing of the biotite flakes, accompanied by a reduction in the grain size of the plagioclase laths, has taken place. “Pools” are still found (3 mm. across) but they contain many tiny flakes of biotite (Fig. 2 B). Here quartz is less abundant, intergrowth is not found and felspar is in small irregular grains, or has a tendency to be lath-shaped. The apatite of the original rock has been broken along the transverse parting and tiny needles of apatite, derived from the keratophyre, also occur. The original plagioclase of the dolerite now has the composition Ab$_{96}$An$_4$ but albite rims are not developed. Also the keratophyre solutions, often containing flakes of biotite, have penetrated along the cleavage cracks and reduced the grain size from 3 mm. to 1 mm. or less (Joplin, 1935). Considerable bending and separation of the cleavage blocks has often resulted. The displaced anorthite molecule has not formed epidote or clinozoisite within the felspar, but is most likely responsible for the large quantities of tiny epidote granules in the surrounding matrix.

An analysis of a hybridised dolerite is given in Table II, column II.
A. Considerably hybridised dolerite with keratophyre pools. The albitised basic felspar contains separated epidote and clinozoisite, sometimes showing a zonal arrangement. Occasionally sericite is associated. Uralitised augite is partially changed to biotite with some epidote and only slight scattering of flakes has taken place. Ilmenite is replaced by sphene. ×13.

B. More intensely hybridised dolerite in which less peaceful penetration has caused scattering of the biotite flakes obliterating the original ferromagnesian minerals. Remnants of one are still visible in the south-east quadrant. Reduction in grain size of the felspar is shown. Indication of a "pool" is found in the north-east quadrant. Epidote and clinozoisite are found as tiny granules and some fibrous hornblende is shown. ×13.

Fig. 2. Hybridised Dolerites.

A

B
A slightly different type is produced by the hybridisation of the hornblende-bearing dolerite (Fig. 3 A). The elongated hornblende crystals are first changed to pale green uralite, with the separation of much ilmenite. With increasing hybridisation the uralite is changed to criss-cross flakes of biotite, which is green unless associated with iron ore, when it becomes brown. Scattered grains of ilmenite have an outer rim of brown biotite, and an inner one of sphene. The original zoned plagioclase crystals have been albitionised, and in the core granules of clinozoisite and epidote have developed. Later potash solutions, concentrated towards the end of crystallisation, have produced sericite in the central core and micropertite in the outer zones. Filling the interstices, forcing the plagioclase laths apart, and causing bending of the original hornblende crystals, is material derived from the keratophyre magma. It consists of micropertite, quartz, and albite which often form micrographic intergrowths. The albite generally shows very fine multiple twinning. Healing of cracks in the originally basic plagioclase, by intergrown quartz and plagioclase, is fairly common. In this type there is no rim of albite round the original plagioclase of the dolerite, although it has been albitionised.

(b) Spotted Hybrids.

The spotted hybrids merge almost imperceptibly into the hybrid dolerites on the one hand, and into the keratophyres on the other. They differ from the hybrid dolerites in that the spots are composed chiefly of dispersed flakes of biotite, with associated minerals precipitated from the hybrid magma, and are clearly visible in the hand-specimen. With the introduction of hybrid material they show a gradual increase in size up to a certain point (about 1·5 cm.), when they rapidly decrease. At this point the rock could more correctly be termed a basified keratophyre, for the decrease is due to mechanical disintegration of many small xenoliths in a fluid magma. The spots are not rounded but irregular in shape and tend to be linked together (Fig. 3 B).

These rocks vary from types in which the position, and sometimes the shape, of the original ferromagnesian minerals is preserved by compact masses of biotite with remnants of uralite, to those in which the mineral has been obliterated through the complete replacement of the uralite by biotite and the strewing of these flakes in the
incoming hybrid magma. Epidote is ubiquitous, but much of it is precipitated at a later stage.

The disruption and separation of the originally basic plagioclase laths vary greatly even over a short distance. They are separated by a finely granular matrix (<0.25 mm.) of quartz, albite and sometimes microperthite (micrographic intergrowth is not common), and, where disruption of ferromagnesian minerals has taken place, biotite flakes, iron ore, and epidote are found. The biotite may form compact masses of tiny flakes, while the hybrid material between the plagioclase laths is fairly free from dark coloured minerals, or the spots may spread

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A. Hybridised Hornblende Dolerite. The hornblende is replaced by criss-cross flakes of biotite, iron ore and a few small granules of epidote. Quartz and albite, in places showing micrographic intergrowth, have developed from the incoming keratophyre magma. ×13.

B. Biotite-rich Spotted Hybrid. In this type the original ferromagnesian minerals have been completely altered to criss-cross flakes of biotite with associated epidote. Apatite has been broken into segments. Within the spotted area the felspar has been reduced in grain size. Some scattering of biotite flakes has taken place. ×13.
out for considerable distances in the hybrid rock. A reduction in grain size of the plagioclase similar to that described for the hybridised dolerites occurs within many of the spotted areas. As in the previous types, the biotite and associated epidote and iron ore have been largely derived from the original ferromagnesian minerals of the dolerite, and the changes noted in the hybrid types are also present here, with biotite in much greater abundance. The green amphibole which crystallised from the hybrid magma in the altered dolerite is only occasionally found, and only one specimen with slightly altered uralite and hybrid hornblende has been collected. The formation of epidote granules within the originally basic felspar laths is present only in types closely related to the hybridised dolerites.

Ilmenite is altered almost entirely to compact masses of brown sphene, small grains of pyrite give place to hematite or are surrounded by it, and square crystals of magnetite remain unchanged. Grey cellularapatite derived from the dolerite is found, together with considerable quantities of clear, needle-shaped, and rod-like crystals of apatite from the hybrid magma; the latter is most noticeable in association with the spotted areas. As in the hybrid dolerites, sericite is sometimes present in the altered plagioclase to the exclusion of albite. Purplish brown tourmaline forms crystals and columnar aggregates up to 1.5 mm., which occasionally show slight radiating structure. Pleochroism is marked, O = dark brownish blue, E = light purplish brown, O > E, orientation negative. It is present in small quantities in both spotted hybrids and hybridised dolerites. Analyses of two spotted hybrids are given in Table II, columns III and IV.

(c) Hybridised Keratophyres.

The spotted hybrids pass into hybridised keratophyres where mechanical disintegration by the hybrid magma has produced complete strewing of the small dolerite xenoliths (Nockolds, 1933). The ferromagnesian minerals representing dispersed xenoliths occur in small clots consisting of biotite, epidote, magnetite, and ilmenite (almost completely changed to sphene). Attached to these clots are strings of biotite flakes, epidote, and iron-ore granules, which extend out between the laths of felspar and closely resemble structures of similar origin in the Dhoon granite (Nockolds, 1931). The biotite ranges in colour from fairly
dark brown to bluish green, over very short distances; the former is usually associated with iron ore and is probably a more ferriferous type. For the brown variety, \( X = \text{straw yellow}, \ Y = \text{brownish grey}, \ Z = \text{deep greenish brown}; \) green variety, \( X = \text{straw yellow}, \ Y = \text{greenish grey}, \ Z = \text{deep green}. \) For both types \( X < Y < Z. \)

The originally basic felspar may contain flakes of green biotite along the cleavage cracks, which is due either to chloritic material contained in the felspar or to hybrid material introduced. At other times it is clear except for kaolinisation, and is very much like the type which has developed from the hybrid magma. Occasionally reduction in grain size has occurred.

Surrounding these remnants of solid dolerite are the minerals developed from the hybridised keratophyre. The composition of the plagioclase ranges from \( \text{Ab}_{91} \) to \( \text{Ab}_{99} \) and is probably due to slight basification. Generally, however, these minerals are similar to those described as the keratophyre (see p. 165).

(iii) Veins and Other Late-Stage Phenomena.

In all the hybrids, particularly in the spotted types, irregular patches (<1 mm. to >3 mm. across) consisting of albite, clinozoisite, epidote (sometimes with allanite), quartz, and occasionally calcite are developed. When only small quantities of solutions were available these minerals were deposited in the interstices; when large quantities were present, replacement of the earlier-formed minerals occurred. The potential epidote molecule was the most active and selectively replaced both felspar and ferromagnesian minerals. The albite molecule at this stage played but little part in replacement and gave rise to albite in the interstitial areas.

Where carbonates occur they form irregular masses associated with the altered ferromagnesian minerals, or fill cracks in the felspar and sometimes partially replace the latter mineral.

The allanite is associated with the yellow epidote and forms either groups of radiating crystals which sometimes fill interstices, or prisms up to 0.5 mm. long. Twinning is occasionally shown and zoning is well marked with a dark core which shows signs of corrosion. It is a golden brown colour, \( X = \text{light brown}, \ Y \) and \( Z = \text{deep reddish brown}, \ X \wedge c = 33^\circ, 4\gamma' - 4\alpha' = 0.021, \) orientation negative, and the optical character is indefinitely positive (Fig. 4 A-D).
Where there were still greater quantities of solutions, concentration into cracks, probably produced as a result of cooling, took place. Thus in different parts of the intrusion, epidote, epidote-albite, quartz-epidote-albite, and quartz-epidote veins were formed. The epidote veins range in width from 0.05 to 3 mm. and consist of epidote and clinozoisite. In the larger ones radiating intergrown crystals occur and in the smaller the minerals are granular.

The epidote is yellow and markedly pleochroic, with a sporadic separation of iron which leaves it bleached and more like clinozoisite. At times a parallel arrangement of veins is shown, and dislocation of the plagioclase laths indicates that the veins are true displacement types. The larger ones have irregular boundaries and are at least partially chemical replacement types, although the original position may have been determined by fracturing (Fig. 5 A). Hereafter they will be referred to as replacement veins.

Albite-epidote veins are rare, and consist of a hypidiomorphic granular rock which is medium grained. The felspar is most commonly in tabular crystals, but is sometimes granular. Chequer-albite is also fairly commonly

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**Fig. 4. Allanite.**

A. Allanite (heavily stippled) and epidote showing a parallel, radiating arrangement in an interstice.

B. In this interstice a fibrous radiating mass of allanite terminates in small well-formed epidote crystals.

C. A zoned crystal of allanite surrounded by granular epidote.

D. A twinned crystal of allanite surrounded by epidote.
Fig. 5. Types Produced by Late Hybridisation Processes.

A. The epidote vein is largely a chemical replacement type penetrating a hybridised dolerite. Along the edges of the vein epidotisation of felspar has taken place and a few large patches of epidote are found. The uralitised augite is only slightly attacked. Ilmenite is replaced by sphene and some fibrous actinolite has developed. ×13.

B. A portion of a hybridised dolerite in which epidotisation has been carried almost to completion. The felspar is almost entirely altered and the uralite shows replacement by larger grains of epidote. Much actinolite has developed. The apatite is the grey variety and belongs to the original diorite. ×13.

found, sometimes surrounding the more normal type. The epidote is yellow and pleochroic and has either an interstitial or an ophitic habit, while it occasionally fills cracks, indicating that it crystallised fairly late (Fig. 6 B). Considerable quantities of ilmenite are present with white borders of leucoxene, together with a few tiny flakes of yellow pleochroic biotite, both of which appear to be incorporated from the surrounding rock. A green hornblende is found with increasing development towards the edge of the veins; this is described below (see pp. 176-7). In the centre of the vein it forms long needle-like crystals, up to 1 mm. in length, which are often grouped into
sheath-like bundles; near the edge a hornblende-albite rock is developed, in which the former mineral occurs in fibrous masses (Fig. 6 C).

Quartz-epidote veins are fairly common, and range from 0.1 mm. to 15 mm. in width. They seem to be mainly displacement-veins filling already formed cracks, and the larger ones contain fragments of felspar from the surrounding rocks. The epidote forms prisms up to 2 mm. long in the larger veins and is granular in the smaller ones. The quartz sometimes occurs in slightly elongated grains, oriented so that their long axes are parallel. This would indicate that the veins have been sheared and are therefore pre-granite in origin. Quartz-epidote-albite veins occur in places, but they resemble the quartz-epidote types, except that the felspar is present in very small amount.

The introduction of these veins gives rise to much the same mineralogical changes in the surrounding rock as those already mentioned in connection with the interstitial solutions. First, the plagioclase of both doleritic and hybrid origin is replaced by granular masses of epidote. Along the edges of the vein complete epidotisation of felspar may take place, but further away it becomes gradually less intense, taking place only along cleavage cracks (Fig. 5 A). With more profound epidotisation all the felspar is replaced and the uralite is also attacked and replaced by slightly larger, more intensely pleochroic grains of epidote, indicating an addition of iron from the uralite. At this stage there appears a fine fibrous green amphibole which may be fairly closely associated with the replaced hornblende, or may develop in what is now completely altered felspar (Fig. 5 B). As already stated it is found along the edges and even towards the centre of the albite-epidote veins, and also in areas where there has been chemical replacement around interstices. It is

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**Fig. 6.**

A. Part of a zone of apatite crystals produced in one of the spotted hybrids a short distance from an invading keratophyre vein. The crystals tend to be elongated parallel to the length of the vein. ×13.

B. An Albite-Epidote Vein. The albite is in rather tabular crystals and the epidote is largely interstitial. Actinolite is present as small acicular crystals. ×13.

C. The edge of the albite-epidote vein B, showing masses of fibrous actinolite crystals (including several cross sections) associated with albite and ilmenite. ×13.
optically negative, with positive elongation, $Z'=19°$, $a'=1.626$, $y'=1.652$. Pleochroism is very marked: $X=light yellow$, $Y=brownish green$, $Z=bluish green$, $X<Y<Z$, which indicates that it belongs to the actinolite group.

(iv) Dynamically Metamorphosed Types.

The results of shearing are evident in all the rock-types in the north-western part of the area (see map). The direction of schistosity is $65°$ W. Away from this zone of definitely schistose rocks less intense movement is indicated by localised strain, which has produced small elongated patches of very clear recrystallised felspar and quartz, in which the associated biotite flakes show a parallel arrangement. Generally the plagioclase is somewhat contorted and may show slight clouding (MacGregor, 1931). Since all three main types have been influenced by dynamic changes it is obvious that both intrusions took place prior to the faulting.

(a) Keratophyres.

These rocks appear to have contained considerable quantities of dispersed xenoliths and are most likely hybrid types. The plagioclase, much of which is of doleritic origin, has not been completely recrystallised, shows "nibbled" edges, and contains a few granules of epidote and zoisite and dusty-like inclusions, probably of iron ore. The surrounding material, which probably represents the original keratophyre magma, has recrystallised to tiny grains of quartz, plagioclase, which is sometimes finely twinned, and orthoclase. The biotite is in very tiny, slightly greenish flakes and shows the normal straw-yellow to brownish grey pleochroism. These have been segregated into long wavy, string-like masses, associated with finely granular ilmenite (Fig. 7 A). At times these have been forced to wrap round the remnants of felspar crystals and give the rock a slight augen structure.

(b) Spotted Hybrids.

The spots shown in the unsheared types are still preserved but they are rather elongated (Fig. 7 B). In the field these rocks are further from the zone of stress and show less, schistosity than the dolerites. Much of the biotite is of a colour similar to that in the above types but is in larger flakes. It is closely associated with finely granular...
optically negative, with positive elongation, $Z \wedge c = 19^\circ$, 
$\alpha' = 1.626$, $\gamma' = 1.652$. Pleochroism is very marked; 
$X =$ light yellow, $Y =$ brownish green, $Z =$ bluish green, 
$X < Y < Z$, which indicates that it belongs to the actinolite 
group.

(iv) **Dynamically Metamorphosed Types.**

The results of shearing are evident in all the rock-types in 
the north-western part of the area (see map). The direction 
of schistosity is N. 65° W. Away from this zone of 
definitely schistose rocks less intense movement is indicated 
by localised strain, which has produced small elongated 
patches of very clear recrystallised felspar and quartz, in 
which the associated biotite flakes show a parallel arrange-
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(b) **Spotted Hybrids.**

The spots shown in the unsheared types are still preserved 
but they are rather elongated (Fig. 7 B). In the field 
these rocks are further from the zone of stress and show less 
schistosity than the dolerites. Much of the biotite is of a 
colour similar to that in the above types but is in larger 
flakes. It is closely associated with finely granular
quartzofelspathic material and shows a parallel arrangement. Remnants of yellow epidote and hornblende remain, but the latter is mostly altering to biotite. The felspar crystals from the original dolerite show either recrystallisation round the edge, or "nibbling", while others have been bent or broken with the formation of clear untwinned bands across them. Apatite and masses of ilmenite, usually accompanied by sphene, show either bending or considerable fracturing.

(e) Dolerites.

The dolerites show intense shearing and in hand specimen could be called biotite-schists. The microscope, however, reveals fairly considerable quantities of hornblende of metamorphic origin and the rock is more truly a hornblende-biotite-schist.

The plagioclase is much more recrystallised than in the previous types, its shape having been obliterated, and only a few rounded masses 1 mm. to 1.5 mm. remain, surrounded by granular material. Epidote and clinozoisite, so noticeable in many of the hybrids, are not found, but many tiny rounded flakes of green biotite or minute fibrous and radiating needles of hornblende have developed. The recrystallised colourless material is composed of quartz and plagioclase.

The alteration of the uralitised ferromagnesian mineral shows some variation. Often a crystal is broken into as many as three pieces, and along the shear-planes biotite has developed. Masses of small actinolite crystals are developed about the uralite crystals, usually elongated parallel to the direction of schistosity. Aggregates formed in this way give a somewhat poikiloblastic appearance to the rock. Where orange-brown biotite occurs only between the fibrous uralite crystals it may have developed during previous hybridisation. However, where biotite forms large masses, it would seem to be of metamorphic origin, and at times biotite develops along one side of a mass of uralite and actinolite along the other (Fig. 7 C).

As in the previous type elongated flakes of biotite are segregated into irregular bands and patches, often in conjunction with magnetite and ilmenite which has been segmented and surrounded by sphene. The colour of the biotite ranges from pale greenish yellow to bright orange-brown; pleochroism of the former is $X = $pale straw yellow, $Y =$greenish grey, $Z =$greenish brown, and of the latter
X: bright straw yellow, Y reddish orange, bright orange; for both X < Y < Z.

The metamorphic hornblende forms small elongated prisms which are often grouped into large aggregates (2 mm. long), but minute needles form radiating aggregates. This amphibole shows marked cross-parting, is bluish green, with strong pleochroism. X = greenish yellow, Y = yellow-green, Z = deep blue-green; elongation negative, optical character positive, ZAc = 17''. It is thus most likely an actinolitic variety. The apatite is broken along the cross-parting, separation sometimes being as much as 1 mm.

The outcrops near the mine dump in Por. 43, Par. Wuuluman, represent a type which contains no biotite and shows no directional structures. Fibrous green hornblende has replaced the original ferromagnesian minerals, and in the remnants of piagioclase and the surrounding recrystallised patches needles of the same hornblende have developed in great numbers. The needles in the piagioclase were probably produced as a result of clearing of the original felspar such as is described by MacGregor (1931). Skeletal ilmenite shows great alteration to sphene.

Another unsheared type occurs a little north of the south-west corner of Por. 98, Par. Wuuluman, but it shows less recrystallisation than the type near the mine-dump. Here the original ferromagnesian minerals of the dolerite have been replaced by a fibrous green hornblende and occasional biotite flakes. The albitic piagioclase shows

Fig. 7. Dynamically Metamorphosed Types.
A. Keratophyre. The criss-cross flakes of biotite have been arranged in clots and bands associated with limonite. Much recrystallisation of the felspar is shown, remaining crystals showing irregular rounded edges. X 13.
B. Spotted Type. Although the spotted areas are still visible they are somewhat elongated and the biotite flakes show a parallel arrangement. (Contrast with 2, B.) The piagioclase crystals are cracked and strained and in places partially recrystallised. X 13.
C. Dolerite. This is now a hornblende-biotite-schist. The original uralite is replaced by both biotite and actinolite (showing cross parting) often within the one mass — S.E. quadrant. Actinolite and biotite develop within the recrystallised felspars. All minerals, including the masses of ilmenite, largely changed to sphene, show a parallel arrangement. The cellular apatite is much fractured and the segments separated. X 13.
X = bright straw yellow, Y = reddish orange, Z = bright orange; for both $X < Y < Z$.

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only slight signs of recrystallisation, but contains grey patches of minute grains of iron ore and occasionally hornblende (see p. 165).

4. Petrogenesis.

(1) Mineralogical Transformations.

The foregoing petrological descriptions serve to indicate that there were two influxes of keratophyric magma, first, one rich in soda, and, secondly, one in which potash was more concentrated (see Table I). The second was responsible not only for the formation of biotite within the hybrids but also for the introduction of orthoclase into the sodic felspar of both the keratophyre itself and its hybrids.

The earliest change in the augite and hornblende of the original dolerite is the development of uralite, and at the same time green hornblende is precipitated from the hybrid magma. The uralitisation may, in part, be a metamorphic change, but generally seems to be a hybrid adjustment due to the introduction of a fluid magma low in the reaction series (Bowen, 1915). The presence of abundant volatiles probably made possible the development of hornblende in the hybrid magma.

Nockolds (1933) cites a number of examples to show that soda diffuses more rapidly than potash into a rock in which lime is more plentiful than magnesia, and it may be this fact which accounts for the early development of uralite in the hybrid dolerites, to be followed slightly later by biotite. This is borne out somewhat by chemical analyses. The change from uralite to biotite results in a further release of lime and at the same time the anorthite molecule is being released from the felspar. For a short period this increase in lime in the rather small quantity of solution introduced, together with iron probably released from the ilmenite-sphene reaction, seems to make possible the development of a more actinolitic hornblende as blue-green edges to masses of uralite and hornblende from the hybrid magma, which have not yet been replaced. Thus for a short time biotite and hornblende remain in equilibrium in the magma. With a slightly greater increase in the potash content of the invading solutions, there is a decrease in the proportion of lime contained, and all the hornblende is rendered unstable and is gradually replaced by biotite. Complete alteration is found only in the most acid of the spotted hybrids.
The original basic plagioclase has been almost completely albitised and around these cores new albite has been deposited from the first soda-rich magma invasion. The fate of the released anorthite molecule is variable. So far as the plagioclase is concerned it is either removed or deposited as clinozoisite and epidote. When removed into the hybrid magma it is stored up until its saturation point is reached. This may occur while the rock is still largely liquid. However, it is more usual for the anorthite molecule to remain in solution until the rock is partially consolidated, when it takes part in late hybridisation changes. The formation of epidote, clinozoisite, and albite in zones in the plagioclase may be due to hydrothermal metamorphism during the early stages of the injection of keratophyre solutions, or to the direct result of hybridisation. Where sericite is found to the exclusion of albite it seems most likely to be a hybrid change. In the Dhoon granite, Nockolds (1931) has a rather similar association, which he has attributed to the fact that the felspar could not react quickly enough and ceased to be in equilibrium, with the result "that the soda more or less completely replaced the lime, which was thrown out as zoisite." Laitakari (1918) and Eskola (1921, 1922) conclude that in a low-temperature environment with an abundance of water, albite and epidote will arise rather than a more basic plagioclase. At Ben BuUen, John (1935) finds a similar association due to the assimilation of lime. At Wuuluman the highly sodic aqueous magma probably prevented the formation of plagioclase, in which case the reaction was closely related to that indicated by Nockolds, Laitakari, and Eskola. These alterations brought about by sodic solutions closely resemble deuteric alterations; in this case, however, they are not residual liquors of a crystallising rock-mass but are related to a later intrusion.

There is much evidence available to show that after a considerable amount of hybridisation had taken place the rocks were subjected to further alteration. This took the form of intense epidotisation of felspar, of uralite, and, to a smaller degree, of biotite. It was brought about by solutions trapped in interstices in the almost consolidated rock and also by veins, the positions of which were probably determined by cooling cracks, although considerable chemical replacement is found along the edges of the larger ones. Clinozoisite and allanite accompany the

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<tr>
<td>Precipitation from the magma.</td>
<td>Introduction of soda.</td>
<td>Introduction of potash also.</td>
<td>With increase in soda and potash and therefore a decrease in lime.</td>
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<tr>
<td>Hornblende—&gt;Biotite.</td>
<td>Uralite—&gt;Biotite.</td>
<td>Accompanying these changes.</td>
<td>All hornblende—&gt;Biotite.</td>
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<tr>
<td>The precipitation of green hornblende.</td>
<td>Ilmenite—&gt;Spheic and Biotite.</td>
<td>Blue hornblende.</td>
<td>Accompanying this change Ilmenite almost completely replaced by spheic and biotite.</td>
</tr>
<tr>
<td>The Original Plagioclase.</td>
<td>Basic plagioclase albitised. Anorthite molecule removed. This may be precipitated as epidote from the hybrid magma.</td>
<td>Basic plagioclase albitised with the development of epidote and clinozoisite in situ.</td>
<td>Disintegration and disruption of the xenoliths in the fluid magma giving clots of biotite with epidote and iron ores.</td>
</tr>
<tr>
<td>Mechanical Introduction of Keratophyre Solutions.</td>
<td>Slight separation of plagioclase laths and the formation of rims of albite.</td>
<td>Wider separation and the formation of &quot;pools&quot; of keratophyre material. Generally injection is peaceful, but occasionally strewing of biotite flakes results.</td>
<td>More injection and considerable strewing results in the development of dark coloured spots.</td>
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<tr>
<td>Veins and Late Stage Phenomena.</td>
<td>Introduction and/or concentration of epidote-bearing solutions which may replace plagioclase and the ferromagnesian with the release of MgO. This makes possible the development of actinolite which is often associated with the epidote.</td>
<td></td>
<td>Complete disintegration of included xenoliths.</td>
</tr>
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STUDIES IN ASSIMILATION.
The original basic plagioclase has been almost completely albitised and around these cores new albite has been deposited from the first soda-rich magma invasion. The fate of the released anorthite molecule is variable. So far as the plagioclase is concerned it is either removed or deposited as clinozoisite and epidote. When removed into the hybrid magma it is stored up until its saturation-point is reached. This may occur while the rock is still largely liquid. However, it is more usual for the anorthite molecule to remain in solution until the rock is partially consolidated, when it takes part in late hybridisation changes. The formation of epidote, clinozoisite, and albite in zones in the plagioclase may be due to hydrothermal metamorphism during the early stages of the injection of keratophyre solutions, or to the direct result of hybridisation. Where sericite is found to the exclusion of albite it seems most likely to be a hybrid change. In the Dhoon granite, Nockolds (1931) has a rather similar association, which he has attributed to the fact that the felspar could not react quickly enough and ceased to be in equilibrium, with the result "that the soda more or less completely replaced the lime, which was thrown out as zoisite". Laitakari (1918) and Eskola (1921, 1922) conclude that in a low-temperature environment with an abundance of water, albite and epidote will arise rather than a more basic plagioclase. At Ben Bullen, Joplin (1935) finds a similar association due to the assimilation of lime. At Wuuluman the highly sodic aqueous magma probably prevented the formation of plagioclase, in which case the reaction was closely related to that indicated by Nockolds, Laitakari, and Eskola. These alterations brought about by sodic solutions closely resemble deuteritic alterations; in this case, however, they are not residual liquors of a crystallising rock-mass but are related to a later intrusion.

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epidote. The soda at this stage was rather inactive. These solutions evidently represent the last remnants of the keratophyre magma modified by the addition of material from the dolerite, chiefly lime and iron derived from the different hybrid reactions. This intense epidotisation released considerable quantities of magnesia from the ferromagnesian minerals, which united with the potential epidote molecule, and possibly some of the potential albite molecule, to form the fibrous actinolite, found where intense alteration has taken place and along the edges of the larger invading albite-epidote veins. The development of this amphibole at a time when the rocks were largely consolidated and considerably cooled must have been made possible by the presence of volatiles which were undoubtedly present.

(ii) Chemical Discussion.

For the purpose of comparison the analyses I-V of Table II have been recalculated so that equal volumes may be compared. There is considerable difference in density between the original altered dolerite and the hybrid types; the slightly hybridised dolerite is 1·34% denser, the hornblende-biotite spotted hybrid 4·36% less dense, and the biotite-rich spotted type 6·04% less dense. The first has therefore been recalculated to approximately 100·91% and the other two to 95·86% and 93·52% respectively. The altered dolerite and the keratophyre have been recalculated to 100% (see Table III).

Compared with the original altered dolerite the hybrids generally show a marked decrease in iron, MgO, CaO, TiO₂ and MnO, and an increase in Na₂O, K₂O, SiO₂ and P₂O₅. The position of Al₂O₃ is somewhat variable. With the exception of number two there is a steady increase in the Na₂O/K₂O ratio as the dolerite is approached, possibly due to the excess of lime over magnesia (Nockolds, 1933).

The keratophyre has not been compared with the hybrids, as all specimens show signs of assimilation and its original composition is not known.

It has been shown that augite is first replaced by hornblende and later this is replaced by biotite, also the originally basic plagioclase is replaced by albite, often with the removal of the anorthite molecule. Nockolds (1935) has shown that the nature and amount of material introduced from the hybrid magma, and subtracted from the
### Table II.

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I. Altered Dolerite, South of road in Por. 43 Par. Wuuluman. Anal. E. M. Basnett.


V. Keratophyre. On top of hill, Por. 69, Par. Wuuluman. Anal. E. M. Basnett.


Xenoliths, will vary with the rate at which the different reactions take place. Small quantities of MgO are set free in the ferromagnesian changes, and CaO is also released, but much more abundantly in the change from hornblende to biotite. The release of these two constituents from the original ferromagnesian mineral enables the hornblende to develop from the hybrid magma, and probably accounts for the development of a more actinolitic variety when the
Volatiles have been introduced, and these have undoubtedly been derived from the keratophyre magma.

(iii) Physical Conditions of the Invading Magma.

In the Wuuluman Creek Intrusion we are not only dealing with a number of xenoliths which have been incorporated in a fluid magma, but also with a rock-mass which has been saturated with keratophyre solutions giving rise to a considerable mass of hybrid rocks.

It is evident from the development of albite and epidote in the basic plagioclase, the formation of epidote veins, and the abundance of apatite, that the invading keratophyre contained considerable quantities of volatiles and was at a relatively low temperature. It seems most likely that the amount of penetration which has taken place could have been possible only if the dolerite itself still retained some heat. Again, as already stated, it seems likely that the keratophyre magma did not penetrate to the surrounding sedimentary rocks, so that whatever heat and volatiles it originally contained would be dissipated more slowly.

The alteration of the original minerals of the dolerite, particularly the ferromagnesian types, would suggest a diffusion of material into the dolerite in advance of the magma, to be followed later by actual mechanical injection. When in small quantities this was rather peaceful, but as the quantity of injected material became greater considerable movement occurred. It was not always related to the amount of material introduced as considerable disintegration is found in the hybrid dolerites.

5. Summary.

The Wuuluman Creek mass has been shown to consist of two separate intrusive types. The younger, a keratophyre, has invaded an earlier mass of dolerite and has produced zones of hybrid rocks.

The mineralogical changes in the hybrid rocks have been shown to be due to the introduction of sodic keratophyre magma, followed by the injection of a keratophyre magma richer in potash. Later changes were brought about around veins and interstices which were filled with solutions containing material released during the hybridisation of the dolerite. The constant development throughout the hybrids of albite and epidote, instead of a more basic felspar, is considered to be due to low temperature conditions and to an abundance of water.

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<tr>
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<td>9.15</td>
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<td>Na₂O</td>
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<td>K₂O</td>
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<td>2.10</td>
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<td>P₂O₅</td>
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<td>0.89</td>
<td>0.41</td>
<td>0.16</td>
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<tr>
<td>MnO</td>
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<td>0.18</td>
<td>0.14</td>
<td>0.07</td>
<td>0.09</td>
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</table>

100.00 100.93 95.84 93.50 100.00

I. Altered Dolerite recalculated to 100%.
II. Slightly hybridised Dolerite recalculated as explained in text.
III. Spotted Hybrid containing hornblende recalculated as explained in text.
IV. Spotted Hybrid rich in Biotite recalculated as explained in text.
V. Keratophyre recalculated to 100%.

Change from uralite to biotite first takes place. The iron and titania for the formation of biotite probably arise from the break-down of ilmenite, while lime is used for the formation of sphene. The formation of hornblende or biotite depends probably on the K₂O content, and possibly also upon the amount of available water. The greater part of the CaO is stored up until late in the hybridisation history. It must also be remembered, however, that in all these types solutions, as such, have entered the hybrid rocks to a considerable degree, and so there has been an actual mechanical addition. The increase in P₂O₅ in the hybrid types is shown in the formation of large quantities of apatite needles within the xenolithic spots and from the hybrid magma itself, the lime being supplied by the reactions already discussed. The presence of much apatite and of small quantities of tourmaline and of pyrites in the hybrid rocks indicates that considerable quantities of
volatiles have been introduced, and these have undoubtedly been derived from the keratophyre magma.

(iii) Physical Conditions of the Invading Magma.

In the Wuuluman Creek Intrusion we are not only dealing with a number of xenoliths which have been incorporated in a fluid magma, but also with a rock-mass which has been saturated with keratophyre solutions giving rise to a considerable mass of hybrid rocks.

It is evident from the development of albite and epidote in the basic plagioclase, the formation of epidote veins, and the abundance of apatite, that the invading keratophyre contained considerable quantities of volatiles and was at a relatively low temperature. It seems most likely that the amount of penetration which has taken place could have been possible only if the dolerite itself still retained some heat. Again, as already stated, it seems likely that the keratophyre magma did not penetrate to the surrounding sedimentary rocks, so that whatever heat and volatiles it originally contained would be dissipated more slowly.

The alteration of the original minerals of the dolerite, particularly the ferromagnesian types, would suggest a diffusion of material into the dolerite in advance of the magma, to be followed later by actual mechanical injection. When in small quantities this was rather peaceful, but as the quantity of injected material became greater considerable movement occurred. It was not always related to the amount of material introduced as considerable disintegration is found in the hybrid dolerites.

5. Summary.

The Wuuluman Creek mass has been shown to consist of two separate intrusive types. The younger, a keratophyre, has invaded an earlier mass of dolerite and has produced zones of hybrid rocks.

The mineralogical changes in the hybrid rocks have been shown to be due to the introduction of sodic keratophyre magma, followed by the injection of a keratophyre magma richer in potash. Later changes were brought about around veins and interstices which were filled with solutions containing material released during the hybridisation of the dolerite. The constant development throughout the hybrids of albite and epidote, instead of a more basic felspar, is considered to be due to low temperature conditions and to an abundance of water.
Some time after consolidation the north-western part of the mass was subjected to dynamic metamorphism, probably as a result of faulting, and the rock types produced have been described.

Recalculated analyses have been made the basis for the consideration of reciprocal reaction in so far as such a discussion is possible.

6. ACKNOWLEDGMENTS.

In conclusion the writer wishes to thank Dr. W. R. Browne and Dr. Germaine A. Joplin for reading the manuscript of this paper, and for their kindly help and criticism. She is indebted also to Miss M. J. Colditz, B.Sc., who assisted with field work and mapping, and to Mr. and Mrs. E. J. Bullock and Mr. and Mrs. E. V. England of Wellington for their hospitality and assistance during field work.

7. REFERENCES.


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