A NOTE ON SOME LEUCITE-BEARING ROCKS FROM N.S.W., WITH SPECIAL REFERENCE TO AN ULTRABASIC OCCURRENCE AT MURRUMBURRAH.

By MADELEINE H. HARVEY, B.Sc.,
Deas Thomson Scholar in Mineralogy (1939),
and GERMAINE A. JOPLIN, B.Sc., Ph.D.,
Department of Geology, University of Sydney.

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I. INTRODUCTION AND PREVIOUS RECORDS.

Occurrences of leucite-bearing rocks described under the general term of leucite-basalts have been recorded from several isolated districts in N. S. Wales. T. W. E. David and J. Milne Curran discovered leucite-bearing rocks near Byrock almost simultaneously. David forwarded his specimen to Judd,[20] who recorded it as the first discovery of leucite in Australia. In the same year Curran[8] published a note on this occurrence and referred also to the discovery of similar rocks about 50 miles to the south of El Capitan. Later David and Anderson,[11] who had accompanied Curran to El Capitan, described and figured specimens from both Byrock and El Capitan. In 1891 Curran[9] described two specimens of " leucite-basalt " from between Harden and Murrumburrah, and in this communication he expressed the opinion that the rock occurred as a flow. A few years later he[10] recorded a dyke, containing basic inclusions and garnets, a mile further south. In 1901 Card[6] described one of the Murrumburrah rocks as a monchiquite and gave an analysis of the rock together with two new analyses of the Byrock and El Capitan types. Later the El Capitan rock was figured by Harker[14] in his " Petrology for Students ".

In 1915 the Geological Survey of N. S. Wales recorded leucite-bearing rocks from Lake Cudgellico and the Condobolin district, and one of these was analysed by W. A. Greig.[13]

Recently a specimen of a leucite-bearing basaltic rock was obtained from a well sunk through granite by Mr. Stevenson of Griffith. This rock was forwarded to the Mining Museum, and the Curator, Mr. H. F. Whitworth, has kindly allowed us to examine it.

In the present paper it is proposed to give further details of the Murrumburrah occurrence and to review other occurrences.

II. Field Occurrence.

Murrumburrah is situated about one mile from Harden on the Main Southern Railway Line at a distance of 240 miles from Sydney. The leucite-bearing rocks occur in an arborescent dyke-like mass cutting granite in Portion 522, Parish of Murrumboola. Several small quarries expose the intrusion and reveal its complicated nature. In most cases the basic magma has made its way along joint planes in the granite, and when following horizontal joints it occurs as tabular sheet-like masses which are sometimes exposed at the surface and resemble a flow. It is probable that the intrusion occurred fairly close to the surface, and but little of its cover has been removed by erosion. Frequently off-shoots from the main intrusion completely surround and cut off blocks of granite, which, though retaining its original texture, becomes very dark in colour. It will be shown that the basic liquid has permeated and reacted with the solid granite of the included blocks. The granite at the contact of the intrusion is hardened but not otherwise altered.

The dyke reported by Curran[10] to contain garnets has not been examined, but the main mass examined by us contains inclusions of ultrabasic rocks as well as large idiomorphic or partly corroded crystals of pyroxene and biotite. These often measure two inches across, and one book of mica measuring four inches has been observed. Numerous cavities and veins filled with chlorite, carbonates, chalcedony and quartz are apparent in the field, and microscope examination has revealed an interesting suite of minerals occurring in this way.

We have not had an opportunity of examining the field occurrence of any of the other leucite-bearing rocks of N. S. Wales, but earlier reports leave little doubt that most of them occur as flows. The discovery of the Griffith rock in a shaft through granite suggests its intrusive nature.

III. Petrography.

(i) The Murrumburrah Occurrence.

In view of the importance of late magmatic activity, it is proposed to describe the normal phase of the rock and to devote a special section to those parts that evidence this phenomenon. The ultrabasic inclusions and the hybridisation of the basic rock by granite will also be described separately.

(*a*) *Normal Phase.* In handspecimen these are fine-grained basaltic rocks with a sub-conchoidal fracture.

Under the microscope they are porphyritic and usually intersertal, but where the magma has cooled quickly in contact with the granite a very fine microcrystalline or cryptocrystalline groundmass has developed, the only mineral to have completely crystallised being magnetite, which occurs in small octahedra (Fig. 2B).

Biotite-bearing and biotite-free varieties are present and these may be subdivided into varieties with and without nepheline; rocks containing both biotite and nepheline are the most common types. Leucite is more abundant in the biotite-free types poor in nepheline and the analysis of such a rock appears in column II, Table I. In general the nepheline-rich varieties are slightly lighter in colour and coarser in grainsize.

Olivine is very abundant in all types and occurs as phenocrysts and microphenocrysts, which are idiomorphic to subidiomorphic and measure from 0·75 mm. to about 0·2 mm. The phenocrysts are often fresh, but the olivine, especially in the vicinity of the veins and cavities, is usually altered to either iddingsite or serpentine. The absence of iron ore inclusions from the pseudomorphs suggests that the original olivine was rich in the forsterite molecule, and this view is strengthened by the high magnesia in the analysed rocks.

Leucite usually occurs as small rounded micro-phenocrysts or as small irregular interstitial grains in the groundmass. In the larger crystals small radially arranged inclusions are conspicuous and alteration to analcite is not infrequent.

Idiomorphic crystals (up to 0·7 mm.) of pyroxene sometimes occur as micro-phenocrysts. These are zoned with an inner greyish-green core, followed by a zone of distinct purple colour and then by a greyish-purple margin. Augite, which is slightly titaniferous and of a greyish-purple colour, is the most abundant mineral in the groundmass, where it occurs in a plexus of small ($<0 \cdot 1$ mm.) prisms or rounded grains.

In the normal nepheline-bearing types nepheline occurs interstitially in the groundmass as poikilitic plates (0·7 mm.). It is often accompanied or replaced by analcite (Fig. 1B). Sometimes, however, tiny idiomorphic crystals surrounded by a plexus of augite and magnetite are developed.

Biotite is a prominent mineral in most types and occurs as small (up to 0·3 mm.) poikilitic plates in the groundmass. X=straw yellow, Y=reddish brown, Z=dark reddish brown, $\alpha' = 1 \cdot 563$, $\gamma' = 1 \cdot 637$. In most cases the cleavage is rather poorly developed.

Magnetite is usually very abundant in the groundmass, where it occurs as perfect little octahedra. The analyses indicate very high titania in these rocks, and, although much of this is contained in the pyroxene, it is possible that the iron ore is a titaniferous magnetite.

No plagioclase has been detected with certainty in the groundmass of these rocks, although a few tests have been made by staining with malachite green. Card[6] was unable to recognise this mineral in the specimen examined by him, but in view of the analysis suggested that a small quantity might be present in the base. Although we do not deny this possibility, we consider that recent work on the composition of the pyroxenes[29] has shown that normative anorthite might easily be contained in the titanaugite which is so abundant in the Murrumburrah rocks.

(*b*) *Late Magmatic Phase.* Fine-grained types immediately adjacent to the granite contact as well as the slightly coarser normal types have been affected by end-stage processes, but in general the fine marginal types are the more susceptible. The late-stage minerals are usually deposited in small veins and cavities of a very sinuous nature and rarely measure more than 8 mm. In the vicinity of these cavities the olivine phenocrysts of the normal rock are altered to either iddingsite or serpentine but the former appears to be the more common. Sometimes the texture of the rock is a little coarser near the veins and in some of the rocks small coarser grained ocelli occur.

In the handspecimen these rocks have a characteristic hackly fracture, and, when rounded amygdules are present, the fractured surface has a knotted appearance. The surface of one type shows small rounded knobs, the size of a pea, which are about an inch apart. Under the microscope it is seen that the nodules contain small ocelli about 1 mm. in diameter. These either consist of an aggregate of small rounded isotropic grains which appear to be leucite or show a border of idiomorphic leucite crystals with inwardly projecting radii of diopside and an infilling of chlorite. In other types small coarse granular ocelli consist mainly of diopside and a little chlorite.

The coarser areas adjacent to some of the veins differ widely in texture. One such patch shows an intergrowth of idiomorphic nepheline crystals (about 0·3 mm.), biotite, and titanaugite which suggests a graphic structure. The nepheline is associated with and partly altered to analcite. Alteration to zeolites and possibly to hydronepheline also occurs. Small stellate patches and tiny sheaves of titan-augite needles are embedded in some of the analcite, which has also been clouded with minute granules of iron ore and tiny needles of apatite. It is believed that the analcite containing pyroxene has replaced nepheline, as these two minerals are such constant associates. Several veins have been noted in which analcite borders carbonates and occurs as an interstitial mineral in the adjacent rock. The grainsize in the vicinity of such a vein is much coarser, and a texture differing from that of the normal rock is developed. Augite is richer in titania and a few millimetres away from the vein the crystals are more closely packed, giving the rock a pilotaxitic texture. Augite prisms are larger than usual and very variable in size, becoming larger in the area of analcite bordering the vein (Fig. 1D). The analcite often contains dendritic inclusions of a chlorite-like material which we have often observed in the nepheline of theralites, and which we believe to be identical with the " grid-like or herring-bone ribs with an interstitial background of poikilitic nepheline " observed by Holmes[17] (p. 95). Holmes suggests that this chloritic material may be chlorophæite. Although we have observed this material only in the analcite of the Murrumburrah rocks, there is evidence to show that it represents analcitised nepheline.

Large idiomorphic crystals of dark brown mica measuring from about ½ inch up to 4 inches in diameter are of common occurrence at Murrumburrah. In the handspecimen resorption is suggested by a rounding off of the crystal

A

B

C

D

Fig. 1. Late Magmatic Types, Murrumburrah. ×14.

angles. It is difficult to prepare slides of this material and its origin has not been satisfactorily determined. In view of the fact that biotite arises as a late magmatic mineral (Fig. 1B), it is possible that this might be the origin also of the abnormally large crystals. The few rather poor microsections available show large optically continuous sections of biotite surrounded by and threaded with smaller flakes arranged in criss-cross fashion. Most of these appear to be separated from the normal rock by nepheline or other late magmatic minerals suggesting an end-stage origin for the biotite. These books of mica, however, represent such a large bulk of material that it seems possible that they may originally have been xenoliths of mica-peridotite or glimmerite which have become mobilised under the action of volatiles and have segregated with other late-magmatic minerals. Holmes has pointed out that biotite is a mineral which is very readily mobilised under pneumatolytic conditions.

Fig. 1. Late Magmatic Types, Murrumburrah. $\times 14$.

A. Cavity in biotite-leucite-monchiquite. The cavity is lined with idiomorphic crystals of nepheline and the centre is infilled with blade-like crystals of titanaugite, dark chlorite clouded with inclusions of iron ore, a little biotite and carbonates. The enclosing monchiquite consists of phenocrysts of olivine mostly altered to iddingsite, in a groundmass of augite microlites with interstitial leucite deep brown biotite and little octahedra of iron ore.

B. Vein through nepheline-bearing leucite monchiquite. A large plate of interstitial nepheline may be seen on the left-hand side of the figure and a plate of analcite is present on the right. The vein is bordered by idiomorphic crystals of nepheline and blade-like or columnar crystals of titanaugite and biotite. The centre is filled with dark chlorite clouded with iron ores, as well as colourless plates of chlorite and skeletal crystals of biotite.

C. Part of a sinuous cavity lined with allotriomorphic grains of nepheline and small acicular crystals of titanaugite. Towards the centre of the cavity hedenbergite is developed instead of titan-augite, and the centre is infilled with carbonates.

D. End of a vein in pegmatitic type. The vein consists of carbonates with irregular grains of calcite mantled with fibrous aragonite. Bunches of carbonate needles (possibly aragonite) are growing into the calcite. The vein is bordered by dark chlorite, which passes out into analcite with dendritic inclusions of (?) chlorophæite. In the immediate vicinity of the vein analcite is interstitial, but at a distance of about one mm. the texture of the rock becomes pilo-taxitic. Prisms of titanaugite are very variable in size and larger near the vein. A cavity lined with carbonates is shown in the N.E. quadrant.

Many of the veins and cavities are bordered with idiomorphic crystals of nepheline in close association with acicular crystals of reddish-brown biotite and pyroxene (see Fig. 1A, B, C). When more than one variety of pyroxene is present titanaugite is deposited before hedenbergite. Diopside, though common, does not appear to occur in cavities with titanaugite, but it is sometimes followed by the variety richer in iron.

The centres of these veins and cavities are infilled with carbonates and/or chlorite, the latter often crowded with minute needles of apatite and tiny grains of iron ore. When both carbonates and chlorite are present the deposition of the carbonate usually precedes that of the chlorite. Calcite is often " dog-tooth " but may occur as irregular grains. Bunches of minute carbonate filaments often appear to be growing from the wall of the cavity into the calcite grain (Fig. 1D). These have not been identified, but it is possible that they may be aragonite. A narrow mantle of fibrous aragonite also appears on the botryoidal surface of the calcite (Fig. 1D).

Yellow stilbite ($\alpha=1 \cdot 494$, $\gamma=1 \cdot 500$) may occur in sheaf-like bundles of radiating crystals on the surface of the calcite.

Chlorite may be colourless, pale green or brownish-green. The refractive index is usually lower than that of Canada balsam. Sometimes a fibrous radiating structure is developed, but the mineral usually occurs in large isotropic flakes.

(*c*) *The Granite Hybrids*. At the immediate contact with the granite the basic rock is chilled and the only recognisable minerals are microphenocrysts of altered olivine and minute grains of magnetite. The large included blocks of granite assume a dark colour, and on microscopic examination it is seen that its minerals are fractured and threaded with magnetite. Felspars are heavily sericitised, quartz strained and fractured, and biotite almost completely pseudomorphed by magnetite. A reddish-brown mineral with high refraction and birefringence occurs sometimes in little rounded grains. This is possibly fayalite.

A little closer to the basic rock, where tongues of the magma have penetrated the solid granite, biotite is entirely replaced by magnetite and may contain small inclusions of olivine ; quartz is surrounded by minute granules of pyroxene which are separated from the comparatively fresh felspar by veinlets of chlorite. Around the biotite there is a narrow rim of very fine trachytic material consisting of tiny microlites of orthoclase, flakes of chlorite, and minute iron ores (Fig. 2A). Incipient red-brown mica occurs in patches in the chlorite. In the handspecimen this rock, with its numerous xenocrysts, resembles a granite in texture, if not in colour, and might be referred to as the granite-hybrid.

Adjacent to the margin of the basic rock the basic hybrid is developed. This also consists of small, though slightly larger, laths of orthoclase in which have been embedded numerous xenocrysts of quartz, felspar and pseudomorphed biotite crystals that have been rifted off from the granite. This rock has an intersertal texture, the dark material between the orthoclase laths being chlorite and pyroxene (Fig. 2B). A little plagioclase is possibly present in this plexus, but none has been positively identified. Xenocrysts of microperthite show a fringe of tiny orthoclase laths in optical continuity with the xenocryst. Plagioclase xenocrysts are usually mantled with a narrow border of orthoclase and remnants of corroded quartz show trails of gas bubbles and a dark border which can be resolved under high power into granular augite, dark chlorite, and iron ore. Holmes observed gas bubbles and coronas of granular augite around the quartz xenoliths in many of the Uganda lavas.

Some of the granite fragments have travelled some distance into the basic magma and have been enclosed as xenocrysts (Fig. 2C). Quartz crystals are much corroded and shattered around the edge, where optically continuous fragments are threaded and surrounded by pale chlorite. The xenocryst appears to have been surrounded first by the titaniferous augite with which the magma was saturated. Prisms of diopside have grown inwards into the shatter zone from this barrier of titanaugite, and these are followed by a growth of hedenbergite which appears to be penetrating the shatter zone from the direction of the corroded xenocryst as well.

(*d*) *Ultrabasic Inclusions.* Fragments of dunite and chromite-bearing harzburgite, and elliptical inclusions of pyroxene are of common occurrence in the basic rock. The xenoliths measure up to about $\frac{3}{4}$ inch in diameter and the pyroxene xenocrysts are often more than an inch in diameter. As pointed out above (p. 425), the large crystals of biotite which are associated with end-stage minerals possibly represent mobilized ultrabasic xenoliths consisting mainly of mica such as glimmerites, but as yet no such inclusion has been identified.

The harzburgite is a coarse-grained rock showing octahedral sections (0·6 mm.) of deep brown chromite associated with olivine and enstatite. Fresh olivine embedded in serpentine is very well developed, and

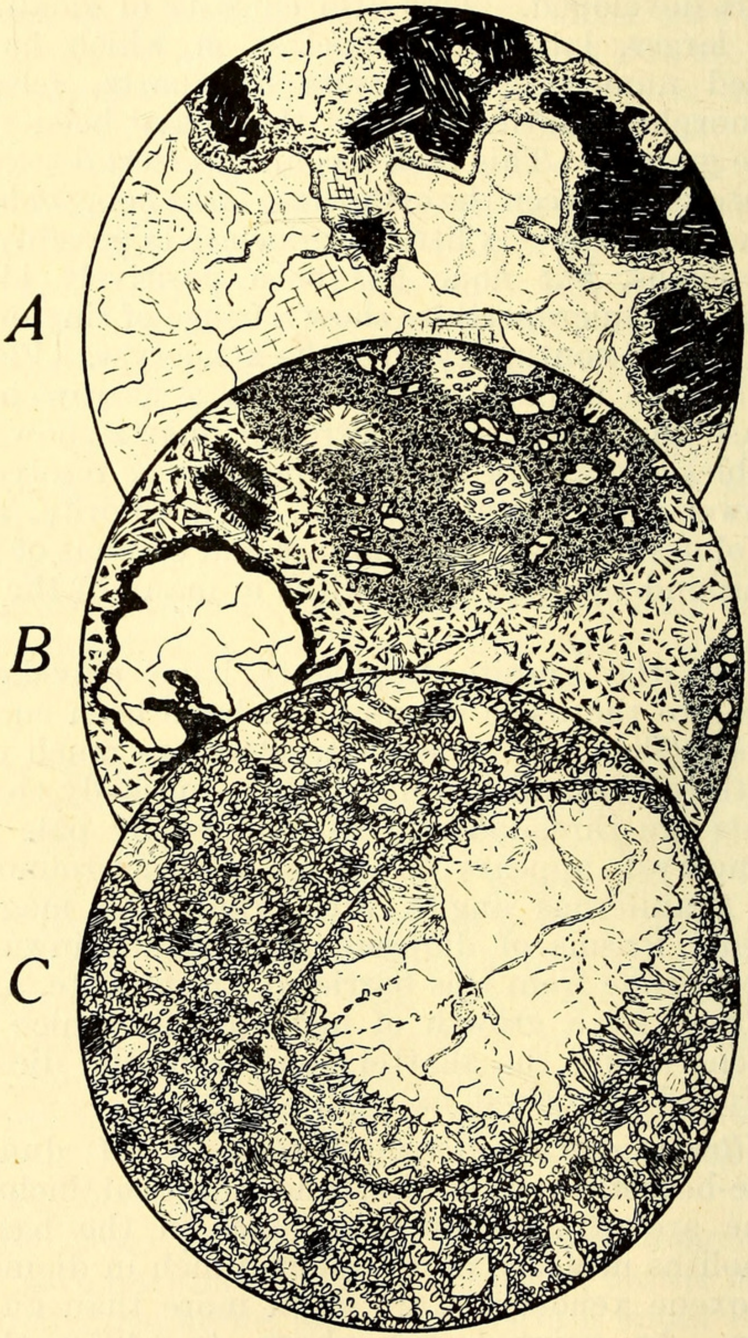

Fig. 2. Monchiquite-granite Hybrids, Murrumburrah. $\times$ 14.

irregular grains of enstatite are always surrounded by a kelyphitic border (Fig. 3A). A little carbonate material is also present.

Occasional xenocrysts of chromite and large skeletons of olivine occur in the basic rock, and it is believed that these represent almost completely disrupted and assimilated xenoliths of harzburgite.

The pyroxene xenoliths were possibly derived from pyroxenites, though no crystal aggregates have been detected. The xenocrysts are usually elliptical and partly resorbed. Under the microscope they appear to have recrystallised and possibly represent the break down of a complex pyroxene into simpler molecules. The centre zones usually have a very small optical axial angle and may be pigeonite. Iron ores have separated along definite crystallographic directions, producing a feather-like pattern. The outer zone of the xenocrysts is titanaugite, which shows no evidence of recrystallisation and appears to be a mantle of later origin (Fig. 3B). The smaller of these recrystallised elliptical pyroxenes are rather reminiscent of the zoned pyroxene-felspar bodies occurring in some of the Hartley gabbros.(19)

The partial analysis of a large pyroxene crystal from Murrumburrah has been quoted by Curran.(10) It is obvious that much of the iron estimated as the sesquioxide is present in the mineral as the monoxide, and the analysed material possibly represents a mixture of pyroxenes, as there are variations of composition within a single crystal. The analysis is useful, however, in giving an approximate

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Fig. 2. Monchiquite-granite Hybrids, Murrumburrah. ×14.

A. The lower part of the figure represents the normal granite, consisting of quartz and felspar. The upper part is the granite-hybrid, showing biotite crystals pseudomorphed by iron ore and surrounded by a " trachytic " border. A few olivine inclusions are present in the biotite pseudomorphs. Corroded grains of quartz are surrounded by a fine-grained corona of augite.

B. Sharp contact of fine-grained basic rock against hybrid-type which consists of a plexus of small orthoclase laths, granules of augite and dark chlorite with large xenocrysts of quartz and felspar. The corroded quartz xenocryst is surrounded by a dark border of granular augite, iron ore, and chlorite.

C. Leucite-bearing biotite monchiquite with xenocryst of quartz. The xenocryst is bordered with granular titanaugite and surrounded by a rim of fractured quartz grains and chlorite into which diopside and hedenbergite prisms have grown out from the titanaugite " barrier " and from the edge of the xenocryst.

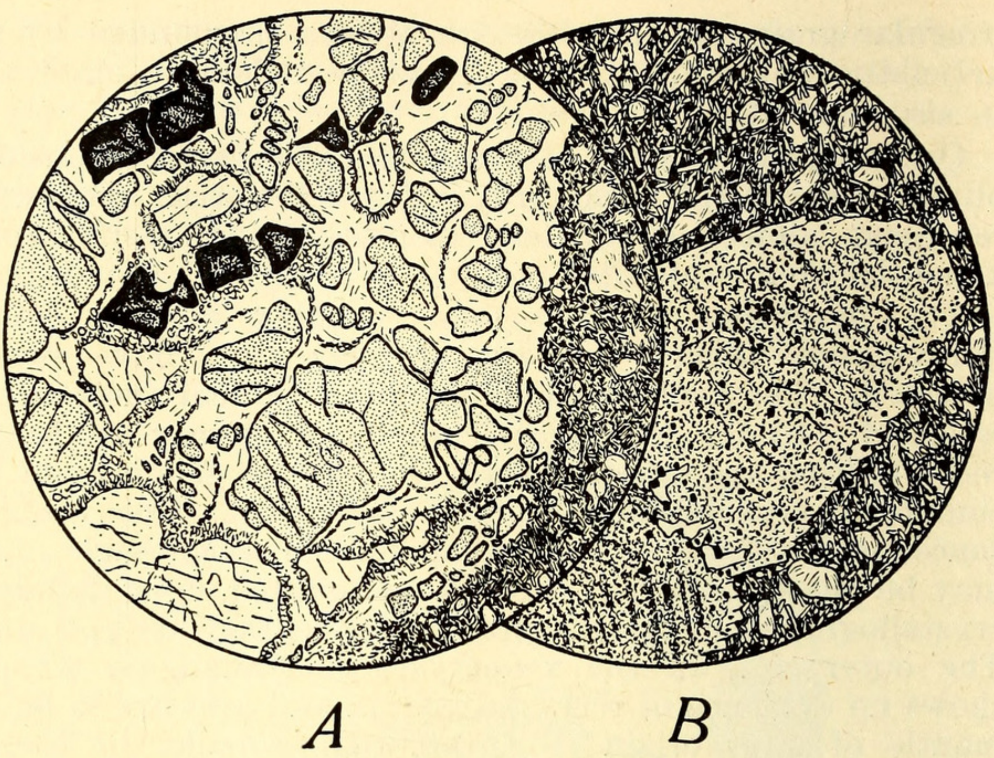

Fig. 3. Ultrabasic Inclusions, Murrumburrah. ×14.

A. Xenolith of chromite-bearing harzburgite consisting of olivine, enstatite, serpentine and chromite. The enstatite is surrounded by a kelyphitic border.

B. Xenocryst of pyroxene in a biotite-free leucite-bearing monchiquite. The xenocryst is roughly elliptical and shows recrystallisation with the separation of iron ores, and is mantled with fresh titanaugite.

idea of the composition of the original mineral, and it is obvious that alumina entered the silica tetrahedron.[29]

(ii) Other Occurrences in New South Wales.

The leucite-bearing rocks from Byrock and from El Capitan, about 50 miles to the south of Byrock, have been described in some detail by other authors,[20, 8, 11] and it is proposed to give only a brief summary here. So far as we are aware the rocks from about the Condobolin centre have not been described, though reference has been made to them by Browne[5] and a rock from Lake Cudgellico has been analysed.[13] The Griffith occurrence has not yet been described and it is found that this rock bears a remarkable resemblance to certain types from the other two areas ; it is proposed to describe these rocks briefly, not under the headings of their respective localities, but as types that have common characters and which may occur in all three localities. Three distinct rock-types have been recognised—one in which poikilitic plates of phlogopite are developed, another in which nepheline is present in the groundmass, and a third with a microcrystalline groundmass, which may represent a chilled marginal phase of either of the other two. All contain some variety of mica.

(*a*) *Type with Poikilitic Phlogopite.* Rocks of this type occur at El Capitan (Fig. 4A), 45 miles S.W. of Condobolin (Fig. 4D) and at Griffith, so it is a widespread type and compares chemically, mineralogically, and structurally with a rock from East Borneo described as a micaleucite basalt by Brouwer[4] (see Fig. 2).

These rocks are rich in olivine, which occurs always as phenocrysts or microphenocrysts in a groundmass of leucite, diopside microlites, iron ore, and large poikilitic plates of bright orange-yellow mica.

The grainsize of the rock from El Capitan, Ungarie, and Griffith varies a little. At El Capitan the phenocrysts are smaller than elsewhere, measuring only about 0·3 mm., and the poikilitic micas measure only about 0·75 mm., but the groundmass is coarser than that of rocks from either of the other localities. Here also the olivine is altered into limonite and carbonates, which seems to suggest that it was a variety richer in iron. In the example 25 miles from Ungarie olivine phenocrysts average about 1·5 mm., and, although most of the mica occurs in rounded plates of about 1·5 mm. in diameter, large elongated flakes may attain a size of 3 mm. (see Fig. 4D). In all these rocks the poikilitic mica is crowded with little rounded crystals of leucite, diopside microlites, and tiny grains of magnetite; the mica is sometimes twinned. In the Griffith specimen the following determinations have been made: $\alpha'=1\cdot555$, $\gamma'=1\cdot639$, Z=light reddish brown, Y=deep orange-yellow, X=pale yellow, and this appears identical with the mineral occurring in the rocks from the other areas. Judd[20] remarked on the occurrence of bright yellow mica in rocks from the Byrock district in 1887, and it has since been mentioned by other authors.[11] Although the optical properties are not identical with those of the titaniferous phlogopite described by Prider,[24] they are certainly closer to this than to normal phlogopite, and the high titania in the analysed rocks suggests a titaniferous variety.

The rocks at Griffith and at El Capitan contain ocelli and cavities indicating the action of late magmatic solutions. The ocelli consist of leucite, diopside, and mica, or of small coarse patches of diopside or leucite

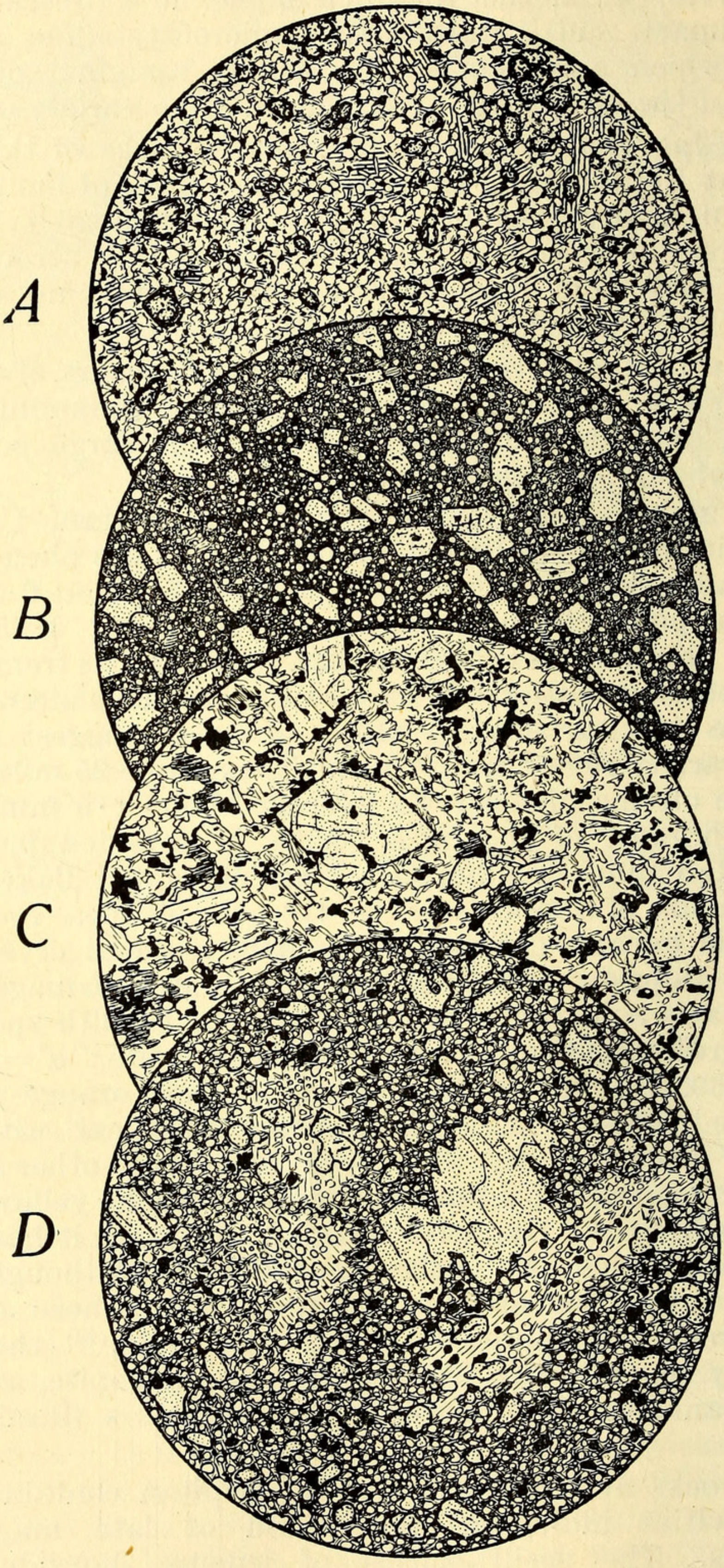

Fig. 4. Mica-leucite Basalts from N. S. Wales. ×14.

alone. In the Griffith rock cavities are filled with chlorite and analcite. Occasional xenocrysts, which were possibly felspar, have been completely analcitised and chloritised, and leucite crystals have grown into them from the groundmass. In the El Capitan rock a cavity containing a peculiar amphibole is present. Only a few sections of the amphibole occur, and the largest extinction angle measured is 14°, but this probably does not represent a maximum. X = pinkish fawn, Y = chocolate, Z = light chocolate brown; $Y > Z > X$. The elongation is positive and the mineral optically negative. It occurs on the outer edge of the cavity in association with leucite, diopside, and mica, and the cavity is infilled with analcite with a core of chalcedony.

(*b*) *Nepheline-bearing Types.* All the specimens of this type have been collected from the Condobolin or Lake Cudgellico area, and reference to the normative composition shows the higher nepheline in these rocks.[5]

They are all very rich in olivine, which occurs as well formed phenocrysts. It has a positive character indicating a high magnesia content. Sometimes the olivine phenocrysts show glomeroporphyritic grouping and occasionally two crystals show a cruciform intergrowth. In addition to phenocrysts of olivine the rocks may sometimes contain smaller columnar phenocrysts of diopside (Fig. 4C), and a slight parallelism of these suggests a fluidal fabric.

The groundmass of these rocks consists of leucite, nepheline, diopside, iron ore, and small flakes of reddish-brown mica similar to that which occurs in the Murrum-

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Fig. 4. Mica-leucite Basalts from N. S. Wales. ×14.

A. Microphenocrysts of olivine partly altered to limonite and iddingsite occur in a groundmass of leucite, diopside microlites, magnetite, and large poikilitic plates of phlogopite. El Capitan, 50 miles south of Byrock.

B. Phenocrysts of olivine and tiny microphenocrysts of leucite occur in a microcrystalline groundmass of augite and iron ore. A few small patches of biotite are also present in the groundmass. Bygalorie, about 45 miles S.W. of Condobolin. Compare fine-grained type from El Capitan figured by Harker.[14]

C. Phenocrysts of olivine and columnar crystals of diopside occur in a coarse groundmass consisting of leucite, diopside, nepheline, biotite, and iron ore. Lake Cudgellico, 50 miles S.W. of Condobolin.

D. Phenocrysts of olivine are present in a groundmass of leucite, diopside microlites, magnetite, and large poikilitic plates of phlogopite. Near Bygalorie, 45 miles S.W. of Condobolin and 25 miles N.W. of Ungarie.

burrah rocks. The larger of the mica plates are more yellowish in colour and have a tendency to poikilitic development. Though iron ore usually occurs in small octahedra, larger skeletal crystals are sometimes developed, and these suggest ilmenite.

One type from Lake Cudgellico is coarser grained than usual (Fig. 4C), and in this the leucite crystals are seen to contain numerous regularly arranged small round inclusions.

(*c*) *Types with Microcrystalline Groundmass.* An example of this type occurs at Bygalorie to the east of Lake Cudgellico, and Harker[14] has figured a similar rock from El Capitan. These possibly represent marginal phases of the other types.

Phenocrysts of olivine are well developed, and the groundmass consists of small rounded crystals of leucite surrounded by dark material which under the high power may be resolved into magnetite and tiny needles of pyroxene. There is an incipient development of dark reddish brown mica, which occasionally forms distinct small plates (Fig. 4B).

IV. Petrogenesis.

(i) Pegmatitoid and Hydrothermal Stages.

Reference to the section dealing with the late-magmatic types indicates that both high and low temperature assemblages are developed and that these are closely associated in the same cavity or vein. Although the minerals in the following list are not all present in a single specimen, the examination of a number points to a very definite order of succession. Infillings of quartz and chalcedony were often noted in the field, and it was found that these were usually surrounded by soft material and readily weathered out. Unfortunately we appear to have overlooked the collection of this material, and none of the rocks sectioned contains either of these minerals. The field occurrence, however, suggests that they were the last minerals to crystallise at Murrumburrah, and a single cavity containing chalcedony in a rock from El Capitan indicates that it was later than analcite.

Leucite
Nepheline
Biotite, titanaugite or diopside and
  amphibole at El Capitan
Hedenbergite
} Pegmatitoid Phase.

Analcite Natrolite or hydronepheline (alteration product of nepheline) Calcite Aragonite, stilbite Chlorite (?) Chalcedony and quartz	} Hydrothermal or Deuteric Phase.

The first group of minerals, although they occur in vesicles, were deposited at high temperatures, possibly by sublimation. It is of interest to note that leucite has been recorded in the cavities of the Vesuvius lavas, and that nepheline and augite occur in the vesicles of the Capo di Bove nepheline-leucitites. Nepheline occurring in this way has also been recorded in the melilite-basalts of Hawaii[12] and the occurrence of biotite in cavities has been noted in the Eifel tephrites and described and figured by Holmes[17] from the vesicles of the Bufumbira lavas.

The term "pegmatitoid phase" was first introduced by Lacroix[21] to describe those coarse-grained patches and veins of high temperature minerals that other authors[18, 22, 26] have variously described as segregations and schlieren. Dunham[12] has employed the term in describing the occurrence of nepheline and associated minerals in the cavities of the Hawaiian lavas.

At Murrumburrah, as at Honolulu and Prospect, the higher temperature or pegmatitoid stage is followed by the lower temperature hydrothermal or deuteric stage, when water and carbon dioxide were the active agents of deposition. Owing to its small size and probable shallow burial, the Murrumburrah intrusion cooled rapidly and end-stage processes were thus restricted, but it is significant that these late-magmatic types are more abundantly developed near the chilled margin which was rapidly cooling, contracting, and cracking, and where magmatic fluids were finding a means of escape. Had these been trapped in the main body of the rock it is probable that coarser grained and more profoundly altered types would have resulted.

(ii) Hybridization by the Granite.

A limited amount of hybridisation of the basic rock has taken place at its contact with the granite, but owing to the rapid cooling modification has been but slight.

The unaltered granite consists of quartz, microperthite, biotite, plagioclase, muscovite, and minor accessories. In the field the margin of the basic rock is sharp against a dark coloured modified granite. Under the microscope a fine-grained basic rock shows a sharp contact with a hybrid rock which gradually merges into the granite. The hybrid penetrates the granite in minute tongues.

It is obvious that large quantities of iron oxide have been released from the basic magma and this material has completely replaced the biotite of the granite, setting free alumina, potash, and magnesia, which no doubt are precipitated as orthoclase and chlorite in the narrow trachytic rim surrounding the biotite pseudomorphs (see Fig. 2A). Some of the magnesia, together with iron, may form occasional crystals of olivine.

Coronas of diopsidic augite about quartz crystals point to reaction between the solid quartz and the lime and magnesia of the basic magma. The converse of this has been noted at the contact of dolomitic limestones where silica has been introduced from the magma.[27] Quartz xenocrysts surrounded by a corona of augite granules have been noted by Holmes,[17] who has also observed fusion of quartz and orthoclase and the deposition of the glass along cracks in the xenocrysts.[16] At Murrumburrah, however, neither mineral seems to have suffered trans-fusion, and, though isotropic material with a low refractive index occupies cracks, this is believed to be a form of chlorite. Dr. W. R. Browne has drawn our attention to a quartz xenocryst with a corona of pyroxene in the Prospect dolerite, and Benson[3] has figured a very similar structure from a basalt near Tamworth. In the latter case the siliceous material is opal, not quartz, and Benson regards the structure as a vesicle surrounded by pyroxene and infilled with opal, but it seems likely that an original xenocryst may have been altered by magmatic waters (see p. 433).

At Murrumburrah the felspars of the granite are fractured but show evidence of marked chemical stability. Corona structures are absent, and outgrowths of tiny orthoclase laths, which are optically continuous with original crystals of microperthite, indicate that this latter mineral was in equilibrium with the hybridised liquid.

Granules of augite occur in the slightly coarser grained hybrid adjacent to the margin of the chilled basic rock, and this type might be regarded as the modified monchiquite. Both hybrids, therefore, differ from the basic rock in their greater acidity and in their felspar content. Orthoclase is developed instead of leucite, and augite arises in place of the ubiquitous olivine of the normal types. Quartz is not in equilibrium in either hybrid, and where xenocrysts of this mineral occur they are separated from the hybrid rock by coronas of pyroxene.

(iii) Ultrabasic Xenoliths and their Possible Significance.

In discussing the origin of leucite-bearing magmas, Holmes[17] has laid stress on the frequent occurrence of ultrabasic xenoliths, particularly of mica-peridotite. Although we have not identified any mica-peridotites at Murrumburrah, other ultrabasic inclusions are abundant and their scattering and partial resorption suggests that a good deal more of this basic material may have been present originally, and that it has been assimilated by the monchiquite magma. Ultrabasic inclusions have also been noted in monchiquite dykes at Bulli,[15] Gerringong.[2] and Kiama,[25] and they are numerous in some of the volcanic necks of the Sydney district,[1, 23] where they are associated with somewhat sodic basalts.

We have not visited any occurrence of leucite-rocks in N. S. Wales except that of Murrumburrah, but there appears to be no record of such inclusion occurring in them, so we do not feel competent to discuss their origin in the light of Holmes' or any other theory. Moreover, the note on the Murrumburrah occurrence is by no means an exhaustive petrological study, and we feel that it would be unwise to base any conclusions upon our observations there.

The scattered occurrence of leucite-bearing rocks in N. S. Wales was emphasised by Browne,[5] who shows, with the aid of a map, that small outcrops up to fifty miles apart may be grouped into areas which are separated by many hundreds of miles. These rocks cut or overlie granites and Palæozoic rocks, but it is believed that they are all of Tertiary age. Their scattered development points to a unique set of conditions under which they have originated, and their genesis cannot be traced until the origin of the other Tertiary lavas, many of them containing ultrabasic inclusions, has been worked out.

V. Nomenclature.

Curran[8] first described the Murrumburrah rock as a leucite basalt, and later Card redescribed it as a leucite monchiquite.[6] Comparison of the four analyses of this rock (Table I, columns I, II, III and IV) with the average

TABLE I.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.
SiO_2 ..	39·51	40·10	40·25	41·72	41·14	40·95	43·58	44·50	44·74
Al_2O_3 ..	15·05	13·59	10·83	13·55	12·67	15·37	11·46	11·67	11·82
Fe_2O_3 ..	2·43	4·27	5·30	2·54	4·72	6·36	3·40	2·05	3·89
FeO	9·22	8·11	8·00	8·87	7·25	4·38	9·13	8·90	7·06
MgO	12·39	12·03	12·53	11·56	11·30	10·46	10·80	13·25	14·28
CaO	10·96	10·12	9·64	9·88	12·02	11·67	9·88	10·18	9·61
Na_2O	4·50	3·93	3·76	3·24	2·80	3·97	2·18	2·53	2·16
K_2O ..	1·67	1·28	1·48	1·51	1·27	1·26	2·13	2·91	2·51
H_2O+ ..	2·13	2·71	2·58	2·01	2·60	3·93	2·40	0·44	0·40
H_2O- ..	0·24	0·35	0·78	0·39	0·74	0·86	0·47	0·12	0·10
TiO_2	2·19	2·32	2·74	2·26	3·46	0·25	3·32	2·55	2·10
P_2O_5	nd.	0·91	0·73	1·09	—	0·09	0·95	0·62	0·66
MnO	0·10	0·13	0·30	0·13	—	tr.	tr.	0·16	0·19
CO_2	abs.	abs.	1·14	1·53	0·08	—	tr.	0·05	0·21
etc.	—	—	0·32	—	—	0·29	—	0·50	0·28
	100·39	99·85	100·38	100·28	100·05	99·84	99·70	100·43	100·01
Less 0 ..	—	—	—	—	—	—	—	0·03	0·05
								100·40	99·96
Sp. Gr. ..	3·04	3·04	3·024	3·03	—	2·932	—	3·06	—

I. Monchiquite. Por. 522, Parish of Murrumboola, Murrumburrah. Anal. Madeleine H. Harvey.

II. Biotite-free Monchiquite, Par. 522, Par. of Murrumboola, Murrumburrah. Anal. Madeleine H. Harvey.

III. Monchiquite, Murrumburrah. Anal. H. P. White. *Rec. Geol. Surv. N.S.W.*, 7, p. 302.

IV. Biotite-rich Monchiquite. (Fine grained marginal type slightly altered by end-stage processes). Por. 522, Parish of Murrumboola, Murrumburrah. Anal. Madeleine H. Harvey.

V. Limburgite. Dark green variety from part of Limburgite-Flow No. II, Kaiserstuhl, Baden. Anal. G. Stecher. W. Meigen and G. Stecher, *Mitt. Grossh. Geol. Badischen Landesanst.*, 8 (1), 1915, p. 170.

VI. Limburgite. Cerro Tacumbu, Paraguay. Anal. A. Lindner. L. Milch. *T.M.P.M.*, xxiv, 1905, p. 214. In W.T. No. 1, p. 693.

VII. Limburgite. No. 4 Quarry, Woodend, Macedon District, Victoria. Anal. R. J. Lewis. E. W. Skeats and H. S. Summers, *Geol. Surv. Victoria*, Bull. 24, 1912, p. 28.

VIII. Ugandite. C. 2809, Muganza. Anal. H. F. Harwood. A. Holmes and H. F. Harwood, The Volcanic Area of Bufumbira. *Geol. Surv. Uganda*, Mem. No. III, 1936.

IX. Murambite. Kanemagufa Valley, South of Mikeno. Anal. Research Dept. Messrs. Imperial Chemical Industries (Fertiliser and Synthetic Products) Ltd., Billingham, Co. Durham. A. Holmes and H. F. Harwood, "The Volcanic Area of Bufumbira," *Geol. Surv. Uganda*, Mem. No. III, 1936.

composition of twelve leucite-basalts (Table II, column IX) shows marked chemical differences. Reference to Table I will show that these rocks compare most closely with certain limburgites and in the absence of glass it seems best to retain Card's name of leucite-monchiquite.

An attempt has been made to use Holmes' classification[17] of the leucite-bearing rocks, and in columns VIII and IX (Table I) two analyses of the African rocks are quoted. It will be seen that the main difference between them and the Murrumburrah rocks lies in the alkalis. In the African examples soda and potash are approximately equal,

TABLE II.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.
SiO_2	43·58	44·68	45·18	42·65	46·04	45·82	46·06	41·71	46·18	46·90
Al_2O_3	8·08	11·43	9·31	9·14	12·40	6·86	10·01	8·55	12·74	16·33
Fe_2O_3	5·00	7·00	6·31	5·13	3·54	6·07	3·17	2·51	5·27	4·22
FeO..	5·77	4·67	4·08	1·07	5·58	1·98	5·61	9·79	5·06	4·14
MgO	12·91	10·25	10·77	10·89	12·60	10·90	14·74	14·65	8·36	5·03
CaO..	8·88	9·44	8·56	12·36	8·38	4·70	10·55	11·74	8·16	9·72
Na_2O	0·90	1·56	1·73	0·90	1·62	0·84	1·31	0·60	2·36	2·75
K_2O	5·99	5·68	6·93	7·99	4·87	8·82	5·14	3·65	6·18	7·58
H_2O+	1·95	2·73	1·01	2·18	} 3·55	0·75	1·44	1·41	} 2·60	} 1·50
H_2O-	1·15	0·77	0·55	2·04		2·40	—	0·16		
TiO_2	4·64	0·84	4·36	1·64	2·20	7·34	0·73	2·15	2·13	1·22
P_2O_5	0·62	0·66	0·51	1·52		1·83	0·21	1·62	0·77	0·50
MnO	0·21	0·11	tr.	0·12		0·10	tr.	0·24	0·19	0·11
CO_2	0·11	0·20	0·17	—		0·08	—	0·16		
BaO	0·32	0·02	0·30	0·89		1·27	0·32	0·50		
etc.	0·14	0·15	0·10	1·59		0·17	0·28	0·38		
	100·25	100·19	99·87	100·11	100·78	99·93	99·57	99·82	100·00	100·00
Loss O	—	0·02	0·01							
		100·17	99·86							
Sp. Gr.	2·897	2·944	2·980	2·857						

I. Leucite Basalt. El Capitan. Anal. H. P. White. *Rec. Geol. Surv. N.S.W.*, *7*, p. 302.

II. Leucite Basalt. Lake Cudgellico. Anal. W. A. Greig. *Ann. Rept. Dept. Mines N.S.W.*, 1915, p. 196.

III. Leucite Basalt. Byrock. Anal. J. C. H. Mingaye. *Rec. Geol. Surv. N.S.W.*, *7*, p. 302.

IV. Madupite. Pilot Butte, Leucite Hills, Wyoming. Anal. W. F. Hillebrand, W. Cross. *Amer. Journ. Sci.*, 1897, *4*, 130.

V. Mica-leucite-basalt. Oeloe Kajan, East Borneo. Anal. A. Pisani, H. A. Brouwer *Pr. K. Ak. Wet. Amst.*, (1), 1909, *12*, p. 151.

VI. Wolgidite (No. 456A, Mt. North). Anal. C. R. Le Mesurier. A. Wade and R. T. Prider, *Quart. Journ. Geol. Soc.*, 1940, *96*, p. 75.

VII. Missourite. Shonkin Stock, Montana. Anal. E. B. Hurlbut. L. V. Pirsson, *U.S.G.S.* Bull. 237, 1905, p. 117.

VIII. Biotite-pyroxenite. Newry Complex. Seeconnell, Co. Down, Northern Ireland. Anal. L. S. Theobald. Doris L. Reynolds, *Quart. Journ. Geol. Soc.*, 1934, *90*, 608.

IX. Average Composition of twelve leucite-basalts. R. A. Daly, *Igneous Rocks and the Depths of the Earth*, 1933, p. 24, No. 107.

X. Average Composition of Nine Leucitites. R. A. Daly, *Igneous Rocks and the Depths of the Earth*, 1933, p. 24, No. 108.

with potash slightly higher than soda, and in the Australian rock soda greatly exceeds potash. The high soda is expressed mineralogically in the presence of nepheline and/or analcite, minerals which are absent from the African ugandites and murambites, though present in some of the other rocks from that region. There seems no reason why a nepheline-bearing ugandite should not occur, and if such a rock be discovered it should compare closely with the Murrumburrah monchiquite.

Plagioclase has not been detected in the Murrumburrah rock, and in this it differs from the murambite. This, however, appears to be a modal rather than a normative difference. Norms have been calculated for the Murrumburrah rocks, but as slight differences of composition appear to be overemphasised, it is considered that a comparison of the norms will serve no useful purpose.

The leucite-bearing rocks from the Byrock and Condobolin districts have always been referred to as leucite-basalts. The three analyses of these rocks indicate great uniformity in their chemical composition, and though the Griffith type has not been analysed it appears to show marked mineralogical and structural affinities to these types. If these analyses (Table II, columns I, II and III) be compared with the average analysis of twelve leucite-basalts (column X) it will be seen that there is a marked difference in their chemical composition. In the N. S. Wales examples the average ratio of K_2O/Na_2O is about 4·5, whilst that of the average leucite-basalt is 2·6. Again magnesia, and often titania, is a good deal lower in the typical leucite-basalts. The higher magnesia and titania in the N. S. Wales rocks finds mineralogical expression in the presence of titaniferous phlogopite, which is a distinctive mineral in these rocks and is absent from the leucite-basalts. The N. S. Wales rocks are, therefore, excluded from the leucite-basalt group on both chemical and mineralogical grounds.

A fairly wide search has been made in the literature dealing with leucite-bearing rocks, and it is found that there are few occurrences that have developed from a magma with a K_2O/Na_2O ratio comparable with that of the N. S. Wales types. The closest analysis is that of a madupite,[(7)] though this rock contains higher lime and potash, indicated by the development of phenocrysts of diopside and phlogopite and the absence of olivine. Mineralogically, therefore, the rocks are dissimilar.

The missourite differs chemically in containing higher lime and magnesia and mineralogically in the absence of mica.

In classifying the rocks of the Western Kimberleys Wade and Prider[(28)] found that they were unusually rich in potash and low in soda, and, though potash is not so high in rocks from N. S. Wales, they show some affinities, both chemical and mineralogical, with the wolgidite described by Prider.

Though a little higher in silica and lower in potash, the mica-leucite-basalt from East Borneo[(4)] appears to compare most closely chemically, mineralogically, and structurally with the N. S. Wales rocks. It seems evident that the magma giving rise to these types, though uniform over a large area in N. S. Wales, was of unusual composition; but it is not desirable to give this rock-type a new name, at least not until a more exhaustive study has been carried out, and in the meanwhile we suggest that the rocks might be termed mica-leucite-basalts, or called by the more general name of lamproite, to several types of which they show resemblance (madupite, wolgidite, etc.).

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