

A KENYA ALNOÏTE AND ASSOCIATED SKARNS*

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ABSTRACT

AXONOTLITE-BEARING alnöite dyke and associated skarns, occurring in a limestone near Muhoroni, Kenya, are described. Micro-metric analyses are given and the mode of origin of the rocks discussed. The conclusion is reached that the xonotlite of the alnöite was produced as a result of the assimilation of limestone in the dyke magma, but that the precipitation of melilite was independent of the assimilation.

INTRODUCTION. Alnöite is a rare basic dyke rock of the lamprophyre family found in alkaline provinces, and characterised by the lack of feldspar and the presence of the lime-rich mineral melilite. It has been regarded as the hypabyssal equivalent of melilite basalt lavas, which though rare, are of more common occurrence. The type was first discovered in 1882 on the island of Alnö off the Westernorrland coast of Sweden; since then examples have been found at few places throughout the world, and alnöites may be accounted a petrological curiosity. The principal localities where they have been found are Polzen in Bohemia (where the alnöite was called luhite), Winnet in Montana, Avon in Missouri, Turij in North Russia, and monticellite alnöite at Isle Cadieux near Montreal. They vary somewhat in their mineral constitution, but are broadly comparable with the original alnöite, of which a modal analysis is quoted on a later page.

Melilite basalts have been described from several localities in Kenya—Mt. Elgon (Prior 1903, p. 250; Odman 1930, pp. 481, 489): Sigowet Hill, Seget valley, Lower Kedowa river, and Nyando river in the Nandi and Lumbwa districts (Prior 1903, p. 250); and near Fort Ternan station where melilite nephelinite also occurs (Maufe 1908, pp. 47, 49). They have also been discovered more recently by official geologists on the Legetet Estates near Muhoroni, and among the Pleistocene Nyambeni lavas of the Meru district. Dyke rocks containing melilite have, however, been described only from Mount Elgon where Odman (1930, p. 505) found two types, melilite nepheline basalts and bergalites, the latter being allied to the alnöites, but containing neither olivine nor pyroxene, and often having a glassy base. But until recently no true alnöite had been found in Kenya, though a rock allied to alnöite was described by Simmons some years ago from Elgon (1930, p. 39).

Towards the end of 1944 the writer discovered a small dyke of alnöite cutting Miocene limestones on the Legetet Estates, near Muhoroni (Fig. 1). The dyke occurs as a few small outcrops on the Northern slope of the limestone hill.

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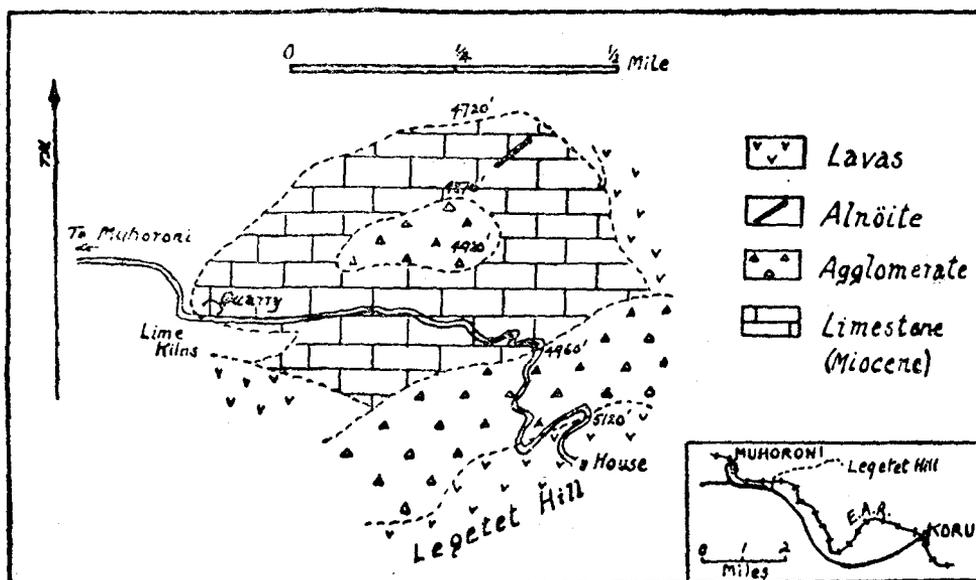


FIG 1. Map of the limestone outcrops on Legetet Estates showing the position of the alnöite dyke.

Exposure is not continuous, but the topographical expression of the dyke, in spite of the few upstanding outcrops, appears to be a shallow depression about 20 feet in width running through the limestone area. On either side of the linear depression the limestone forms low walls, on the northern of which skarns are exposed at the contact of the limestone and the dyke.

LITHOLOGY. The alnöite is a hard, dark grey rock, with abundant phenocrysts of dark brown biotite up to six mm. in diameter, and less frequent black pyroxene phenocrysts up to three mm. in length. The weathered surface is slightly brownish and rough with numerous small protuberances which are due to the superior resistance of the pyroxene grains to erosion. Some of the joints transecting the rock are lined with white or ironstained calcite.

The skarns are somewhat variable according to the amount of silicification they have undergone. One specimen (WM 5)* is a dark grey, hard, fine-grained limestone with a $1\frac{1}{2}$ inch wide band crowded with silicate crystals and magnetite grains up to $2\frac{1}{2}$ mm. across, and with a more sparse scattering of silicate grains outside the defined band. On weathered surfaces the silicate appears dark and often of rounded form, some grains having a suggestion of dodecahedral shape. On fresh surfaces it is black and glassy, or sometimes brownish. Scattered among the dark grains there are also grains of recrystallized calcite up to three mm. in diameter.

* Numbers prefixed by WM refer to specimens in the collection of the Geological Survey, Nairobi.

PETROGRAPHY. Thin sections have been made of the alnöite and the proportions of their minerals measured on a recording micrometer with the results quoted below. Analyses of other alnöites are given beside that of the Legetet rock for comparison. The percentages are volumetric.

ALNOITES.

| | WM 1 | A | B | C |
|------------------------------------|------|-----|----------|------|
| | % | % | % | % |
| nepheline | 6 | Tr. | — | — |
| häüynite | — | Tr. | — | — |
| analcite | 2 | — | — | — |
| cancrinite | Tr. | — | — | — |
| olivine | 1 | 5 | 11.5** | 15.0 |
| augite | 14 | 17 | 6.8 | 13.8 |
| biotite | 22 | 30 | 36.3 | 26.1 |
| amphibole | 2 | — | — | — |
| melilite (and alteration products) | 17 | 33 | 18.7*** | 18.3 |
| garnet | Tr. | — | — | — |
| apatite | Tr. | Tr. | 6.9 | 5.5 |
| magnetite | 12 | 5 | 10.7**** | 9.0 |
| pyrite | — | Tr. | 0.7 | — |
| perovskite | 4 | Tr. | 3.4 | 4.7 |
| xonotlite | 20 | — | — | — |
| calcite | +* | 10 | 4.9 | 7.6 |
| S.G. | 2.95 | — | — | — |

*in melilite.

**pseudomorphs in serpentine.

***approx. composition $\text{Ak}_{41}\text{Ge}_{59}$

****"ores"

WM I. Alnöite. Legetet. Average of two thin sections.

A. Alnöite. Stornaset, Alnö, Sweden. Johannsen 1938, p. 381.

B. Alnöite. North-west of Stornaset, Sweden.

von Eckermann, 1948, p. 105.

C. Alnöite. South of Hovid, Sweden.

von Eckermann, 1948, p. 105.

The principal differences between the Legetet rock and the original alnöite will be readily appreciated — there is considerably less melilite and olivine, a larger proportion of magnetite and perovskite, an appreciable amount of nepheline, and a complete lack of calcite in the matrix, while there is a large proportion of the calcium silicate xonotlite. Some of these differences are not so marked, however, when comparison is made with the von Eckermann analyses. Most recorded alnöites or allied types contain much more olivine than the Legetet specimens, and the presence of xonotlite, which is normally an endogenous mineral found in

limestones near igneous contacts, has not previously been noted in them. On Stansfield's (1923) classification the present rock would be called a bizardite on account of its nepheline content. It is interesting to find that von Eckermann (1948, pp. 98-110) has described alnöites free of melilite, which has previously been considered as an essential constituent. In some cases however, he shows that melilite has originally figured in the rocks, but has been replaced by other minerals.

SKARNS

| | WM 5 | WM 6 | WM 7 |
|-----------------------|------|------|--------|
| | % | % | % |
| garnet (large grains) | 27.1 | 7.1 | 20.3 |
| garnet (granules) | 4.4 | 1.6 | 10.4 |
| magnetite | 10.4 | 10.0 | 12.1 |
| pyroxene | 0.5 | Tr. | 0.8 |
| biotite | — | Tr. | Tr. |
| apatite | 2.1 | 0.6 | 2.2 |
| zeolites | — | Tr. | 1.8 |
| analcite* | — | 1.1 | — |
| perovskite | Tr. | — | — |
| calcite (by diff.) | 55.5 | 79.6 | 52.4** |
| S.G. | — | — | 3.16 |

*in a veinlet.

**including some hydrated iron oxides.

The variation in the size distribution of the garnet in the first and last examples is striking in view of the otherwise similarity of the analyses. It is equally remarkable that the second specimen, though much less silicated than the other two, has an almost identical iron ore content, suggesting that little of the iron introduced during metasomatism has been fixed as iron oxides. This is supported by a chemical analysis of nearby limestones showing 6.06 per cent Fe_2O_3 , which would yield a little under 9 per cent of Fe_3O_4 (magnetite) on reduction.

In thin section the alnöite is a markedly handsome rock with its numerous poikilitic porphyroblasts of biotite (Fig. 2a). The rare *olivine* is fresh and clearly much replaced by the biotite, or more rarely, the augite, in which it is usually enclosed (Fig 2b). The largest grain was probably not much more than one mm. across, and most appears as rounded granules in biotite. It is colourless and optically positive, i.e. it is an iron-poor chrysolite. The *biotite* is sensibly uniaxial and has dichroism X pale straw (very rarely patchily light green), Y=Z yellowish brown, sometimes with a pinkish tinge. Most crystals are markedly poikilitic, but rare large crystals have inclusion-free cores, surrounded by intensely poikilitic outer zones. The biotite occasionally

fingers minutely into the enclosed melilites. The *pyroxene* is augite and occurs in crystals up to $3\frac{1}{2}$ mm. in length. Many are roughly idiomorphic, but the faces of the crystals are ragged, and occasional grains have fantastic shape indicating extreme corrosion. The crystals are colourless or pale green with weak pleochroism, X almost colourless, Y=Z pale green, or sometimes slightly yellowish. The extinction, $Z \wedge c$, is 54° , and the optic axial angle estimated from the isogyres is $+2V=60^\circ$. Many crystals have an irregular outer zone with a few degrees difference of extinction from the core, though often there is no difference of colour between the two portions of the crystals. Occasionally crystals are multiple-zoned, again with no colour differentiation. More rarely there are overgrowths, a core crystal having different orientation from apparently similar augite that has enclosed it. Some crystals have narrow oblique zones of polysynthetic twinning. Many are replaced irregularly at their margins by pale green amphibole. Inclusions consist of iron ore, occasionally nepheline, and biotite, some crystals being markedly "sieved" by the last. On none, however, have biotite coronas developed.

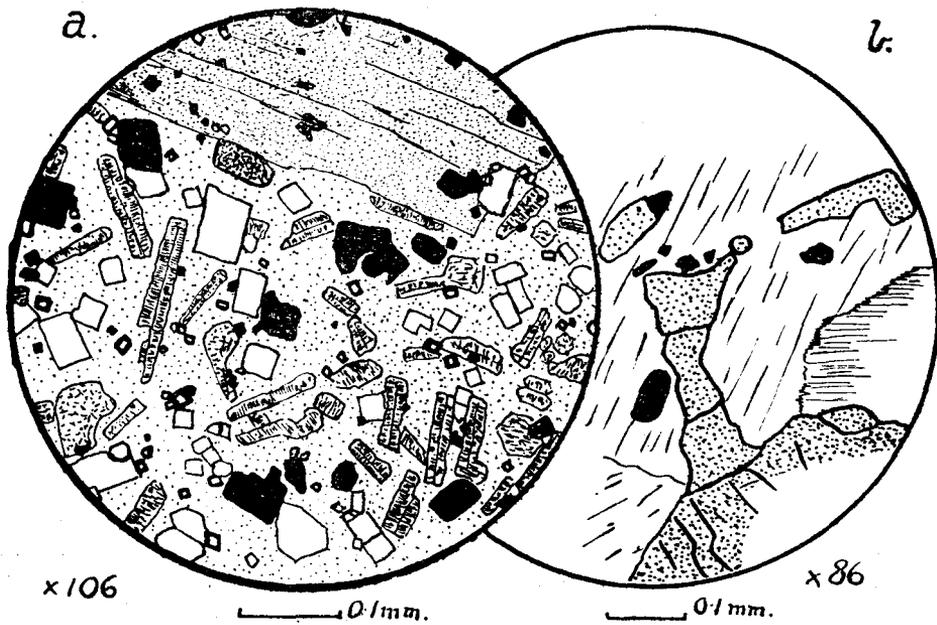


FIG 2. Microscope drawings of a thin section of the alnöite, Legetet Estates. WM 1.

a. Augite in upper part. The remainder of the field is a poikilitic biotite crystal (wide stipple) enclosing idiomorphic nephelines (white), corroded melilites (central crack and lines), perovskite (heavy borders or heavy stipple), and magnetite crystals and grains.

b. Olivine (stipple) enclosed in biotite. The separate fragments of olivine are in optical continuity.

The *melilite* occurs as colourless or, when altered, yellowish tablets, which are most conspicuous when enclosed in biotite, though they also occur elsewhere. The melilite rarely encloses nepheline or is enclosed by it, but none was seen included in the augite. Most sections are narrow oblongs, but some rounded hexagonal or irregular basal sections are also present. The oblong sections always exhibit a central basal cleavage, with, at right angles to it, numerous fibres of an alteration product which may be partly juanite, a hydrous lime magnesia alumino-silicate (Larsen and Goranson 1932, p. 354), but which is probably largely calcite, as the rock effervesces patchily with dilute hydrochloric acid though no recognisable carbonate can be seen in the slides. The degree of replacement by the fibres is variable and is sometimes complete. No peg structures were observed. The crystals vary in size up to 0.3 mm. diameter and 0.03 mm. thickness and are often somewhat corroded, and on occasion intensely. Optically the crystals are negative, and exhibit blue grey or light grey normal interference colours. The maximum birefringence measured was 0.0062, suggesting a composition, in simplest terms, approximating 75 per cent gehlenite, 25 per cent akermanite, and that the molecule is poor in ferrous oxide (Tilley 1929, p. 350). The crystals are apparently unzoned.

Nepheline occurs as square, oblong, or more rarely hexagonal idiomorphs, which again, though they occur elsewhere, are most conspicuous when enclosed in biotite. Some crystals in biotite have their edges well-rounded, and others in the xonotlite matrix of the rock are ragged remnants of original crystals. Occasionally grains occur in the pyroxene. The prisms generally range up to 0.1 mm. in length and are rarely as much as 0.2 mm. The crystals are clear except for occasional small doubtful inclusions.

The *xonotlite* forms a matrix for the minerals mentioned previously, and occurs as radiate fibrous and tufted aggregates. Optically it is positive with small optic axial angle, and has straight extinction and positive elongation. The birefringence is between 0.010 and 0.015, and the refractive indices lie between 1.56 and 1.61, one being a little over 1.5855.

The *perovskite* is mostly present as sharply idiomorphic octahedra up to about 0.45 mm across, but also as irregular grains up to 0.15 mm. When small it appears colourless, but larger grains are brownish yellow, or rarely the more characteristic pinkish brown tinge of perovskite. It is usually anisotropic though without lamellar twinning; smaller grains appear to be isotropic. Rarely it is enclosed in magnetite, and in one case it was seen to have moulded on nepheline and to have penetrated between that mineral and biotite.

Magnetite occurs in grains and octahedra up to 0.1 mm. across, lying in all the other minerals, though often the pyroxenes are devoid of them or have magnetite grains developed only along their edges. Occasionally it occurs as thin seams lining nepheline-biotite contacts, and forms partial coronas around perovskite crystals. Clouds of minute granules are also present in places. *Apatite* is present as small slender prisms in the biotite and as rarer stouter grains associated with analcite. Only one doubtful

grain of garnet was noted — a light brown melanite type, enclosed in biotite.

The *analcite* forms colourless isotropic interstitial patches up to 0.3 mm. across (cf. Bowen 1922, p. 31; von Eckermann 1948, p.99). Associated with the analcite and xonotlite are small patches of a *cancrinite*-like mineral. It is uniaxial and negative, with moderate birefringence.

The remaining mineral of the alnöite is the *amphibole*, which is fibrous and secondary, and occurs mainly as fringes on the augite, though small isolated tufts and fibrous crystals also lie among the matrix minerals. The colour is variable, pleochroism being X light green, Z pale green or X bluish green, Z light green. The extinction is $Z \wedge c = 24^\circ$.

Paragenesis of the alnöite minerals. Several of the minerals present corroded outlines towards the biotite and there can be no doubt of its late development. The general scheme of crystallization of the various minerals may be set out as follows, overlap of the mineral names indicating overlap of their period of formation—

| | | | |
|-----------|-------------|-------------|---------------|
| olivine | | | |
| augite | | perovskite | |
| nepheline | — biotite — | ? magnetite | — xonotlite — |
| melilite | | | |
| | | cancrinite | |
| | | — analcime | |

The position of the melilite may be contrasted with that of the St. Monique (Quebec) alnöite (Stansfield 1923, p. 437), in which it is represented as being later than the mica, and without idiomorphic shape. In the alnöitic rocks of Polzen melilite crystallized prior to the pyroxene, sometimes to its exclusion (Stansfield 1923, p. 449).

Minerals of the skarns. The skarns have a much simpler constitution than the alnöite. Textures are granular and crystalloblastic, the *carbonate* forming a matrix for the other minerals. Much of it is fine-grained granular and dusky, but some has recrystallized as coarse, clear grains.

The most striking feature of the *garnet* is its occurrence in two generations, as megascopic grains, and as minute crystals and grains which often occur as profuse clouds in certain portions of the sections. The granules are yellow or dusky and usually idiomorphic or "rounded," ranging between 0.006 and 0.03 mm. in diameter. There is occasionally a suggestion that macroscopic garnet grains have been formed by the coalescence of granules. The large grains are variable in shape ranging from idiomorphic to angular non-idiomorphic. The colour is also variable; most grains have a colour between light yellow and strong yellow, but there are occasional brown crystals and others are colour-zoned. Some grains have incomplete brown borders, but occasional grains have brown cores and rarely crystals have well-developed multiple zoning in browns and yellow-browns. Frequently zoning ends abruptly at the sharp edge of a grain, and it is concluded that many of the grains are fragmental. Fragmentation can be seen in some cases, the spaces left by the parting of fragments

being filled by clear recrystallized calcite. Some of the garnets contain numerous inclusions of apatite or pools of calcite. This is best seen in a large crystal in slide WM 5 in which the incomplete outer pale zone is crowded with apatites, the darker zoned core having few. In another case garnet has penetrated apatite in irregular growths.

The refractive index of a specimen of the garnet was kindly determined by Mr. J. F. Robinson of King's College, Budo, as 1.886 (at 22°C), indicating that it is a yellow andradite (though probably containing a little of the grossularite molecule), and where brown a titaniferous andradite, perhaps in the extreme even melanite. It is mostly isotropic, though occasional grains are birefringent along cracks.

The *magnetite* of the skarns varies from idiomorphic to irregular in shape. Occasional grains have been fractured and subsequently healed by calcite. Some include small apatites and patches of calcite, and are themselves rarely included in garnet.

The *pyroxene* is scarce, and insufficient is present for accurate determination of its identity, but it is possibly an aegirine-augite, most of it being notably pleochroic from light green to yellow green, though rare grains are almost colourless. The optic axial angle is 80°. Though occasional porphyroblasts remain entire, most of it consists of much-resorbed relics, and some is partly replaced by dusky calcite. One grain in slide WM 6 is surrounded by a corona of garnet granules (cf. Iron Hill uncomphagrite, Larsen 1942, p. 10) and is much darkened by secondary iron ore.

Apatite is a common accessory, and is occasionally large. It is often irregular and frequently enclosed in the garnet, but more rarely in magnetite and pyroxene. Some occurs in pools of recrystallized calcite, and larger grains enclose shreds of calcite.

Biotite was found as small crystals, as small aggregates of crystals, and as scattered shreds. The colour is variably light brown or green. *Perovskite* was noted in only one slide where it occurs as small pinkish brown crystals. The *zeolite* present is generally indeterminate though possibly in one case, where associated with calcite in a veinlet, it is natrolite. The *analcite* also occurs in a veinlet.

The paragenesis of the main introduced or recrystallized minerals of the skarns appears to be—

apatite — pyroxene

—magnetite.

g a r n e t

The possibility of the long-continued crystallization of the garnet is indicated by the large zoned crystal containing apatite inclusions mentioned above.

Petrogenesis. The question of the mode of development of the alnöite is best approached through that of the skarns. The chemical composition of the unaltered limestones not far from the dyke is known, and may be roughly translated into percentages of minerals as — calcite 85%, hydrated

iron oxides and manganese oxides (mainly iron) 9½%, apatite 3%, silicates 2½%. The nature and amount of the materials introduced to form the skarns can be accurately known only when the garnet has been analysed. In view of the minerals formed, however, it can be reasonably assumed that the principal radicles introduced were SiO₂ and Fe₂O₃. These together with lime from the limestone gave rise to the garnet, carbon dioxide escaping. Titanium must also have been introduced to form the melanitic garnet, as there is little titania in the limestones. It is probable too that a small amount of soda passed from the dyke to its walls, assisting in the formation of the small amount of soda pyroxene and zeolites.

The zoning of the garnets of some of the skarns is taken to indicate pulsatory motion of the materials deriving from the dyke. It is also further indication that the titania required for the more melanitic portions of the crystals was most often not derived by abstraction from the limestone.

The fragmentation of the larger garnets is considered as having arisen by mechanical disruption of the dyke wall rocks after their formation, followed by recrystallization of much of the surrounding carbonate, so that fractures are no longer visible in it. The resorption and alteration of the pyroxene probably occurred at this stage. The small garnets of the matrix must then have been formed by the fluids from the dyke. An intermediate stage at which fracturing of the walls could occur may possibly be explained by the incidence of metasomatism of the limestone ahead of the dyke and along a fissure up which it was forcing its way, fracturing taking place when the dyke moved up into the already permeated zone.

Turning to the alnöite, there is no indication that it did not initially crystallize from an alkaline melt or a mixture of melt and crystals. The presence of a considerable proportion of xonotlite (5CaSiO₃.H₂O) and perovskite suggests, however, that during emplacement limestone was assimilated. The presence of melilite would also be taken by some authors (e.g. Simmons 1930, p. 40) as indicating that limestone had been assimilated, but as Bowen has shown (1928, p.267), that is not necessarily true. In fact, if it is assumed that the original magma concerned was of a type suitable to crystallize as nepheline basalt, as seems reasonable from the general constitution of the dyke and the nature of lavas of the same volcanic sequence, there would be sufficient lime available to account for all the melilite. The nepheline basalt of Fort Ternan, for example, contains 11.96% of CaO (Johannsen 1938, p.343), whereas it can be calculated that the lime in the alnöite, exclusive of that held in xonotlite, is probably not far from 11%. Nevertheless there is no doubt that in some cases the solution of limestone in magmas has led to the production of melilite rocks (Tilley 1929).

Bowen (*loc. cit.* p. 259) has shown that in the case of alnöites from Quebec and Montana there is "no evidence . . . that there was ever a liquid corresponding in bulk composition with the final product." In the case of the first he indicated that the rock consisted originally mainly of

olivine and augite, which were then attacked by an alkaline fluid, in part at least the interstitial liquor, leading to replacement by biotite, monticellite, melilite and perovskite. In the present case it seems probable that a similar process has taken place, the alkaline fluid being the residuum after crystallization of olivine and pyroxene, though the possibility of a flux of materials from the parent magma cannot be disregarded. The alnöite must, however, contain roughly the same amount of potash as the nepheline basalts of the area, and it seems unlikely therefore that an accession of new alkaline liquid was necessary for the reactions to take place, the residual liquors of the original magma being sufficient for the purpose.

The process of evolution may be conceived as having taken the following steps :—

1. The original magma is assumed to have been the equivalent of nepheline basalt, which on intrusion consisted of crystals of olivine and probably pyroxene in a basic alkaline fluid. (It should be noted that the Basement System lies at shallow depth below the Miocene deposits on the *Legetet Estates*, and the magmas that gave rise to the lavas and dykes must have passed through it, but there is apparently no sign in either the effusives or the dyke that the magmas were affected by it).

2. After emplacement in the lower part of the dyke-chamber augite would continue to crystallize, olivine being resorbed during the process. At the same time the composition of the remaining liquid would become more and more alkaline until nepheline could precipitate. Before nepheline had completed its crystallization the temperature of the mass was sufficiently decreased for melilite, probably containing an appreciable proportion of the soda-melilite molecule, to begin to precipitate, nepheline and augite being resorbed concurrently. The latter reaction would lead to a re-introduction of magnesia and titania into the liquid, on release from the augite. The liquid remaining would then be a water-bearing solution containing mainly $(K, Na)_2O$, Al_2O_3 and SiO_2 .

3. During stage 2 and as the liquid became more alkaline, limestone would be dissolved from the walls of the dyke, leading to an enrichment in lime, most of the CO_2 escaping.

4. At this stage reaction would begin to take place between the already precipitated crystals and the residual liquid. Biotite, as can be seen in the slides, replaced olivine, augite and melilite, and to a less extent nepheline. The reactions may be considered individually as they concerned each mineral —

- a. olivine — biotite would form by the addition of $(K, Na)_2O$, Al_2O_3 and H_2O from the liquid, with expulsion of some MgO and FeO .
- b. augite — biotite would form by the addition of $(K, Na)_2O$, Al_2O_3 , MgO and H_2O , with the liberation of SiO_2 , CaO , Fe_2O_3 , and perhaps TiO_2 .
- c. melilite — biotite would form by the addition of $(K, Na)_2O$, Al_2O_3 , $FeO(Fe_2O_3)$ and H_2O , with the liberation of CaO .
- d. nepheline — biotite would form by the addition of K_2O , $FeO(Fe_2O_3)$ and H_2O , with expulsion of Na_2O and Al_2O_3 .

No precise evaluation of the net result of these exchanges can be made without knowledge of the chemical compositions of the minerals, and the amounts of each originally present. But it may be reasonably supposed that the solution from stage 3 would now have exhausted its supply of K_2O and probably of most of its Al_2O_3 , but would have become still more enriched in CaO , together with enrichment in FeO (Fe_2O_3), SiO_2 and TiO_2 , there being little change in the Na_2O content. The enrichment in silica would account for the intense corrosion of some of the nepheline in the ground-mass of the rock.

5. During the formation of the liquid of stage 4 the passage outwards of SiO_2 , $FeO(Fe_2O_3)$, TiO_2 , and small amounts of Na_2O and possibly a little Al_2O_3 in ionic form into the surrounding limestone is postulated. Reaction with the minerals of the limestone would lead to the formation of the garnet of the skarns, and the little sodic pyroxene would develop. Early in this process it seems probable that the apatite of the limestone was first brought into solution and then reprecipitated, while at a somewhat later stage the inherent iron oxides were recrystallised as magnetite grains. At the same time magnetite and perovskite would be crystallizing from the liquid in the dyke chamber.

6. From the liquid then consisting largely of a solution of CaO and SiO_2 , the hydrated lime silicate, zonotlite, would precipitate until the solution was largely consumed.

7. The final stage is represented by the crystallization of the remains of the fluid in what "open" spaces remained, the products being conchritite and analcime, principally the latter. A little of the final fluid escaped into the walls where it crystallized as zeolites or as analcime in veinlets. It is assumed in addition that the replacement of pyroxene by hornblende also occurred at this late stage, when the temperature had fallen considerably, though there is no positive evidence to indicate in what part of the sequence it falls.

Such a process accounts for the unique constitution of the alnöite with its matrix of lime silicate and the constitution of the skarns, and at the same time supports Bowen's contention that a liquid excessively rich in lime is not essential for the precipitation of melilite.

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