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Melilite-Nepheline Basalt, its Olivine-Nodules, and Other Inclusions from Nagahama, Japan

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With 3 plates and 4 figures

Abstract

An occurrence of melilite-nepheline basalt in Japan has for the first time been observed. The chemical analysis shows that the rock is not very different from the average melilite-nepheline basalt of the world. Numerous inclusions of grained masses, such as olivine-nodules, augite-hypersthene aggregates, and augite-hypersthene-bytownite aggregates, are found in the lava flows. The thermal alteration of the enclosed minerals is notable. Hypersthene and bytownite of the grained inclusions are highly altered, sometimes, in such a way as to suggest a possible case of formation of a nepheline-augite rock. The hypothesis is advanced that the grained inclusions of the nepheline basalts have their origin in a certain, pre-existent magma with a gabbroic composition.

Furthermore, the lava flows contain frequent xenoliths of an altered phyllite with abundant pyrometamorphic minerals. In these xenoliths, trachytic veinlets are sometimes met with, origin of which may be ascribed to reaction between the nepheline-basaltic magma and the xenolithic matter.

Introduction

The occurrences of nepheline basalts are relatively rare in Eastern Asia: Yinge-men,[1] Manchuria and Tangshan,[2] Shantung are the known localities on the continent. In Japan, Nagahama, a suburb of Hamada City, Shimane Prefecture, has long been known as a unique locality for these rocks. There I have recently found melilite in a certain type of these rocks, and so far as I am aware, this is the first known occurrence of melilite in any region of Japan, Korea, or China. The nepheline basalts of Nagahama have numerous inclusions of coarse granular masses consisting of one or more minerals of olivine, augite, hypersthene, and bytownite; on the other hand, the lava frequently encloses xenoliths with the character of a phyllite. Both of the inclusions of the granular masses and

1) B. Koto, Jour. Col. Sci., Univ. Tokyo, **32**, Art. 6, 1–14, 1912.
2) This occurrence was recently known (A. Harumoto, Chigaku (Science of the Farth), **1**, 37–47, 1949).

phyllitic xenoliths indicate various evidences of notable thermal alterations.

Several treatises dealing with the geology of Nagahama and the neighbourhood have appeared,[3] however nothing containing a full treatment of these rocks has been published so far.

In this paper the petrography of the melilite-nepheline basalt, the granular crystalline nodules, and of phyllitic xenoliths are described in some detail. Further, the processes of thermal alteration of the inclusions are interpreted, and the problem of the origin of the crystalline, granular nodules is also referred to.

Fig. 1

3) S. Yamane, Jour. Geol. Soc. Tokyo, **17**, 436–443, 484–491, 1910; **18**, 33–41, 1911.
T. Shimoma, Bull. Otsuka Geogr. Soc., **1**, 99–109, 1933.
W. Ichikawa, Jour. Japan. Ass. Petr. Min. Econ. Geol., **11**, 76–80, 1934.

Geological Sketch

Immediately adjacent and south of the Iwami-Nagahama station on the San'in Railway, lava flows of nepheline basalts including melilite-bearing type occur, covering, an area of about 1.6 square kilometers. The spot is located on a small hill, the highest point of which, Mt. Tukagahara, has an elevation of 181 m. (Fig. 1). The surrounding slopes of the hill are very gentle, and seem to have been very slightly eroded. The lava is underlaid mainly by phyllites (Upper Palaeozoic), and partly by rhyolite and green andesitic tuffs. To the north of the hill the lava extends as far as 20 m. -level above sea, while in the south and southwest, it goes down to a 70 to 150 m. -level. The thickness of the lava flows seems not to be greater than 50 m. for the most part. Small patches of sand and gravel which are nearly horizontally bedded, containing some granite blocks, are left unremoved here and there on the flat-topped portions of the lava-covered hill. These suggest that the lava was once covered with shallow water, and afterwards the covering sediments were almost denudated away, with only small patches remaining.

No fossil evidence is obtainable from the underlying tuffs and the overlying sediments. Though the age of the extrusion of the lava is unknown, it may not be much older than Upper Pleistocene.

Both melilite-nepheline basalt and melilite-free nepheline basalt are to be found, but in the field the former can hardly be distinguished from the latter. The melilite-bearing type can be found sporadically, and it occurs more frequently in the western parts of the lava-flows area. Remarkable exposures of the melilite-nepheline basalt are found in the vicinity of the village of Takano, which lies about one kilometer southwest of the railway station.

Because of the rather thick covering of the soil, the relation of the superposition of the lava flows usually can not be observed; and it is hard to determine the boundaries between the melilite-bearing and melilite-free nepheline basalts. The distribution of the melilite-nepheline basalt is only tentatively represented on the accompanying geological map.

Melilite-Nepheline Basalt

General Remarks

The melilite-bearing nepheline basalt can be distinguished from the melilite-free nepheline basalt only under the microscope. Their field relation is not clearly known, and no evidence can be found to indicate that they belong to their respective lava flows. From the sporadic occurrence of the melilite-nepheline basalt, it seems that both kinds of rocks represent the local differentiates of the same lava flows.

The lava, as a whole, is dark gray in colour, fine and almost aphanitic in megascopic appearance. With the exception of melilite, it always consists essentially of nepheline, augite, olivine, and magnetite. Feldspar is not found at all, except in foreign inclusions of the lava.

The lava encloses olivine-nodules, allied grained masses, and argillaceous xenoliths; and drusy cavities are often found in it. The cavities are microscopic to 10 cm. across in size, and lined with numerous crystals of zeolites and calcite. In the zeolites are found: gismondine ($\alpha=1.540$, $\beta=1.544$, $\gamma=1.549$, $2V[-]=75°$), phillipsite ($\alpha=1.4990$, $\gamma=1.5035$), thomsonite ($\beta=1.528$, $\gamma=1.539$), stilbite ($\alpha=1.507$), natrolite ($\beta=1.487$, $\gamma=1.494$), and analcime.

These cavities are often filled with water which is believed to be of magmatic origin.[4] Similar aqueous inclusions have also been reported in nepheline basalts from north Germany.[5]

Some specimens of the rocks have fairly abundant melilite and may well be called melilite-nepheline basalt, some have the mineral only as an accessory constituent, and some are nepheline basalt without melilite. With the exception of this mineral, their microscopic characters are closely similar to one another.

The following is the microscopic description of melilite-nepheline basalt collected in the vicinity of Takano:

Petrography

Under the microscope (Pl. III, Fig. 2), melilite-nepheline basalt (no. 30) is found to consist of augite 42, nepheline 30, magnetite 18, olivine 7, melilite 3, apatite and picotite>1, each in aproximate volume per cent.

Olivine occurs only as phenocrysts which are usually less than 0.5 mm. in diamter. It is often idiomorphic, but more frequently shows an irregular outline. Penetration-twins (tw. pl. 011) are quite frequently met with. These twins of olivine are sometimes seen in plagioclase basalts, but in nepheline basalts they seem to be more characteristic.

Melilite occurs in two generations. The microphenocrysts of the mineral show characteristic tabular habitus; and their usual sections are roughly rectangular (0.3 by 0.06 mm. at most), and the cores are dark bluish gray, while the marginal zones are whitish gray, in interference colours (Pl. III, Fig. 3). The mineral is easily attacked by hydrochloric acid. Refractive indices of the marginal zone of the crystal are: $\omega=1.6345$, $\varepsilon=1.6295$. The core is slightly higher in refrative indices than the marginal zone.

According to Buddington's diagram,[6] the mineral has a chemical composition of approximately 11 gehlenite: 31 akermanite: 58 sarcolite. Some ferrous iron may also be contained.

In the groundmass the melilite-microlites show almost the same rectangular sections as the phenocrysts, but the zonal growth is usually lacking. Their optical properties correspond to those of the marginal zones of the microphenocrysts.

In some specimens (no. 16, etc.), the melilite shows a faint tinge of yellow

4) S. Tsuboi, K. Sugawara, and S. Oana, Kagaku, **14**, 102, 1944.
K. Sugawara, S. Oana, and T. Koyama, Proc. Acad. Tokyo, **20**, 722, 1945.
5) R. Heinich, N. J. B.-B., **23**, 490f, 1907.
Th. Ernst, Chemie der Erde, **10**, 663, 1936.
6) A. F. Buddington, Amer. Jour. Sci., 5 Ser. **3**, 58, 1922.

in section; and sometimes, minute seams of an alteration product, pale brown in colour, are seen as short striations roughly perpendicular to the longer axis of the rectangular section. These striations tend to be marked in the narrow peripheral areas and along the cracks of the crystals (Pl. III, Fig. 1), covering, sometimes, more or less uniformly the whole areas of the crystal-sections, especially when the grains are small. This structure seems to be advanced by weathering. In rare instances, well-shaped crystals of the melilite are seen projecting into a pore filled with zeolites, showing that the growth of the former crystals was continued to a very later stage of the consolidation of the groundmass.

Nepheline occurs only in the groundmass, as irregular interstitial grains among coloured minerals, but frequently it tends to be equant in shape; the average diameter of the crystals being 0.03 mm. or less. The mineral is fresh and clear except for its frequent inclusions of minute rods or grains of augite and grains of magnetite. The refractive indices of the nepheline are $\omega = 1.547$, $\varepsilon = 1.539$. In some specimens nepheline is often dirty in appearance and has minute brownish striations, and it is sometimes found that the mineral is altered into an aggregation of minute, double refractive grains.

Augite is the most abundant constituent of the groundmass. It occurs as prismatic crystals up to 0.05 mm. in length, and is often twinned on 100. The mineral is slightly green in colour and is almost non-pleochroic. Its refractive index is $\gamma = 1.716$ and $c \wedge Z = 54°$. Occasionally the well-shaped crystals of the augite project into pore-filling zeolites and in some cases the freely-grown crystals with both terminal faces are seen embedded in the zeolites.

Magnetite occurs in subhedral crystals of various sizes.

Apatite is often developed in the microphenocrystic staut prisms, usually stained with dirty black matter.

Picotite is of rare occurrence, sometimes only one or two irregular crystals being found in a single slice. It is usually surrounded by a thick opaque border. The mineral seems to have been derived from an enclosed olivine nodule.

The melilite-nepheline basalt is holocrystalline and porphyritic, the general texture being the same as that of ordinary nepheline basalt. But the aspect in section is often heterogeneous, even in a single slice; thus, small patches with finer texture are often scattered through coarser and lighter areas.

Chemical Composition

The specimen no. 30, described above, has been analysed, and the result is given under 1 in Table 1. For comparison the average composition of the world's melilite-nepheline basalts is given under 2.

The comparison shows that the analysis is lower in silica, ferric iron, and magnesia; higher in alumina, ferrous iron, and lime. Neverthless, the chemical composition of the rock under consideration is, on the whole, of typical melilite-nepheline basalt.

The norms calculated from the analysis differ considerably from the actual minerals given in volume proportion, partly because of the complex chemical compositions of the melilite, etc., and partly because of the difficulty in accurate measuring the proportion of the constituent minerals on account of their minuteness.

Table 1

	1	2		Norm of 1
SiO_2	36.00	37.56	An	13.07
Al_2O_3	12.87	10.08	Lc	8.72
Fe_2O_3	5.55	6.82	Ne	16.76
FeO	9.68	5.94	Wo	6.38
MgO	8.68	15.32	En	4.00
CaO	16.28	13.82	Fs	1.98
Na_2O	3.64	3.11	Fo	12.39
K_2O	1.85	1.53	Fa	6.83
$H_2O(+)$	2.03	2.52	Mt	8.12
$H_2O(-)$	0.59	—	Cs	13.07
TiO_2	1.74	2.66	Il	3.34
P_2O_5	1.55	0.58	Ap	3.63
MnO	0.31	0.06		
Total	100.77			

1. Melilite-nepheline basalt from Nagahama, Japan. A. Harumoto, analyst.
2. Melilite-nepheline basalt, average of five analyses. R. A. Daly, Igneous Rocks and the Depths of the Earth, 1933, p. 25.

Several analyses of the "nepheline basalts" from Nagahama have appeared in the previous treatises.7) It is unfortunate that these are unaccompanied by detailed descriptions of the specimens that have been analysed. Without exception, these analyses are quite low in silica and high in lime (34.98 to 35.96 per cent SiO_2, 13.37 to 14.39 per cent CaO). These seem to correspond more cosely to the chemical compositions of melilite-nepheline basalts than to those of nepheline basalts. E. Becker 8) has pointed out that the silica of melilite-free nepheline basalt is rarely lower than 39 per cent. Of twenty-seven analyses of nepheline basalts collected in Washington's Chemical Analyses of Igneous Rocks (1917), only two are lower than 36 per cent in SiO_2, and one of these two is none other than the "nepheline basalt" from Nagahama.

Olivine-Nodules, Pyroxene-, and Pyroxene-Plagioclase-Aggregates

Olivine-nodules and other coarse-crystalline, granular masses are found as inclusions in the lava. The distribution of the inclusions is rather localized, and they seem to be more frequent in nepheline basalt in which melilite is not conspicuos. In one place, immediately south of Takano village the lava was found to be crowded with inclusions of this type. The inclusions occur usually

7) H. S. Washington, Chemical Analyses of Igneous Rocks, U. S. Geol. Surv. Prof. Paper, 99. 699, 1917.
W. Ichikawa, Op. cit.
K. Sugawara, S. Oana, and T. Koyama, Op. cit.

8) E. Becker, Zeitschr. deutch. Geol. Ges., 59, 403, 1907.

in irregular forms and have an average diameter of 4 cm. or less. In texture they are holocrystalline and even-granular, and on the whole very similar to a dunite, pyroxenite, or gabbro.

According to the mineral compositions, the crystalline masses may be grouped into: (1) Olivine-nodules, (2) Augite-hypersthene aggregates, and (3) Augite-hypersthene-bytownite aggregates. Intermediate types are not infrequent, but no specimens of anorthositic character were found.

Petrography

Olivine-Nodules

Specimen no. 32 is about 3 cm. in diameter, and nearly round in shape. It is sharply separated from the surrounding nepheline basalt, and shows no sign of remarkable alteration, except for a supergene effect of weathering seen as brown staining along the periphery of the nodule.

Under the microscope, it consists almost wholly of olivine, one mm.- grained, with a subordinate amount of picotite (Pl. IV, Fig. 1).

Olivine is anhedral and equant in shape; cleavages are rather well-developed. It is colourless and clear in thin sections, and has practically no inclusions except some undeterminable minute perticles arranged in rows. The olivine shows no penetration twins, characteristic of the phenocrystic olivine of the nepheline basalt. The mineral shows a faintly perceptible lamellar structure, as seen between the crossed nicols, and this structure usually extends not overall the length of an individual crystal. The optical orientions of the neighbouring lamellae show slight differences from others. The sharp demarcations between the lamellae are not seen even in the universal stage. The structure seems not to be of twinning but of translation lamellae.

The refractive indices of the olivine are $\alpha = 1.665$, $\beta = 1.677$, and $2V(+) = 89°$. The chemical composition is about 85 per cent Mg_2SiO_4.

Picotite ranges from 0.5 mm. to very minute grains. In ordinary thin sections it is nearly opaque; the thin edges being translucent and dark brown in colour. It forms interstitial fillings among the olivine crystals, and is of characteristic amoeboid- or suck-like shapes, often with tail-like projections. In some cases two or three crystals of this mineral are seen to be connected with a narrow ribbon of the same mineral. Minute drop-like grains of the picotite are sometimes seen arranged along the boundaries of the olivine crystals. Thus the picotite has the appearance of replacing the material of the olivine along the boundaries of the latter mineral.

In another specimen (Pl. IV, Fig. 2) the olivine ($\beta = 1.677$) attains to 1 cm. in diameter, and contains fairly large crystals of dark green spinel. The subhedral crystals of the latter mineral (up to 1 mm. in diameter) are found partly embedded in a colourless glass that fills the cracks of the olivine crystals. When the spinel is in contact with the groundmass the former has always black borders. The mineral seems not to be primary inclusions of the olivine.

Pyroxene Aggregates

Pyroxene aggregates are found to be very rarely unaltered. Specimen no.

852 is a fairly fresh crystalline aggregate of augite. It is about 4 cm. across, and greenish black in colour. In the dark gray, compact host rock, the nodule is conspicuous by its glittering appearance due to the well-developed cleavages of the coarse-grained augite.

Under the microscope, the mass consists essentially of augite associated with a small amount of hypersthene, both minerals occurring as 1 to 2 mm. -grained xenomorphic crystals (Pl. IV, Fig. 3).

The augite is nearly colourless, unzoned, and is untwinned, diallagic cleavages being well-developed. Its optical properties are: $\beta=1.696$, $2V(+)=57.3°$. The mineral is diopsidic in chemical composition. The augite encloses, though rarely, small grains of ore, and often very minute, globulitic bodies arranged in curved lines. Where the crystals of augite come in contact with the groundmass of the enclosing lava, they are always fringed with newly-developed marginal zones, and the outer margins of the latter are rugged and extend irregularly into the groundmass. The newly-grown parts of the crystals are optically discontinuous from the remaining portions, the former being slightly deeper in greenish colour than the latter, and larger in optic axial, as well as, in extiction angles.

In the majority of specimens of this type, hypersthene is also present in various amounts. Its optical properties are: $\beta=1.689$ and $2V(-)=78°$. From textural relation, the augite and hypersthene seem, in part, to have crystallized side by side. The hypersthene is often much altered.

Pyroxene-Plagioclase Aggregates

This type of inclusion is most frequently met with. Augite, hypersthene, and plagioclase are present in quite variable proportions. As hypersthene and plagioclase have been most affected by the enclosing magma, only a few specimens of this type are seen practically unaltered.

Specimen no. 862 is about 4 cm. in diameter and is irregularly shaped. It is gabbro-like in aspect, plagioclase and pyroxene being present in nearly equal amounts. The boundary against the host rock seems to be sharp.

Under the microscope, the mass is fairly fresh. Plagioclase, hypersthene, and augite are found to be abundant constituents, in the order named. The average diameter of most grains is about 1 mm. or more (Pl. IV, Fig. 4).

The plagioclase (bytownite) is fresh and clear when it occurs in the interior portions of the mass. It is unzoned, and is frequently twinned on albite and pericline laws.

The hypersthene often remains unaltered when the crystals in the mass are situated apart from the contact with the surrounding nepheline basalt. The mineral is fairly pleochroic as usual, and has often customary inclusions which are of dark brown platy fragments, arranged parallel to 010 of the host. The hypersthene is intergrown with monoclinic pyroxene and the bands of the latter mineral are very thin and few in number. In a section nearly normal to the acute bisectrix X of the hypersthene, there are seen two sets of the bands of the monoclinic pyroxene, each having like extinction angles of about 25°, measured on the opposite side from the line separating the bands. In some sections of the hypersthene the intercalated bands of the monoclinic pyroxene are short, tapering out at both ends. The characteristic alterations of the hypersthene are stated in the later pages.

The augite, on the whole, is of the same nature as that in the pyroxene aggregates. In some cases, where the augite crystal comes in contact with the enclosing groundmass, $2V(+)=57.8°$ for the newly-grown fringe of the crystal, and $2V(+)=56.5°$ for the core.

The optical properties of the constituent minerals of the pyroxene-plagioclase aggregates are shown in Table 2.

Table 2

Specimen No.	Plagioclase		Augite		Hypersthene	
	α' (on 010)	Estimated comp.	β	2V(+)	β	2V (−)
33	1.576	An_{92}		56.5°	1.680 (α' on 110)	
851	1.576	An_{92}	1.699	57.5°		74.4°
854	1.576	An_{92}		55.1°		82.5°
853	1.574	An_{88}	1.694	55.6°		
858	1.572	An_{84}		55.4°	1.685	73.9°
861	1.568	An_{76}		56°	1.684	74.5°

Alterations of the Constituent Minerals

Many of the constituent minerals of the coarse-grained masses are found to have been more or less altered by the reaction with the enclosing nepheline basalt magma. The olivine is usually the least altered mineral, while the pyroxenes and plagioclase show various grades of alterations, sometimes completely altering into pseudomorphous aggregates.

Olivine indicates partial melting. Where an olivine crystal is in contact with nepheline basalt, colourless glass is often formed along the boundary or cracks of the mineral. In this glass, small grains of the olivine that have common optical orientation with the main crystal, are sometimes found. This seems to indicate that the olivine has partially melted. In some cases the small grains of olivine are of random orientation to each other, and thus some grains seem to have been formed by recrystallization. Sometimes, vermicular-shaped patches of colourless glass are seen irregularly distributed in the olivine.

Augite usually remains unaltered in grained masses. When, however, the crystals of the augite are situated at the margins of the grained masses, or isolated crystals detached from the masses are embedded in the groundmass, they are often partially melted and sometimes show sieve-structure, the irregularly-distributed pores being filled with colourless glass.

Hypersthene is seen to be more susceptible to the effects of the enclosing magma than augite, and shows various grades of alteration.

(1) The hypersthene, when it occurs in the interior portions of the enclosed masses, is often only slightly altered and has thin altered zones along the peripheries or along the cracks of the crystals. These altered zones are 0.1 mm. or more in thickness and consist of grains or rods of recrystallized hypersthene which

are of random optical orientation to each other, but often the rods are arranged with their longest dimension normal to the margins of the unaltered portions of the crystals.

(2) The hypersthene alters into an aggregate of the grains of olivine (2V[+] =88.7°), associated with interstitial, faintly double refractive colourless mineral (Ng=1.504). The olivine grains are sometimes idiomorphic (Pl. III, Fig. 5).

(3) The pseudomorphs after hypersthene often consist of small platy pieces of augite which are of common optical orientation to each other in a certain area; olivine grains are irregularly distributed among the former pieces, and interstitial colourless mineral is present.

(4) The pseudomorphs consist of augite grains and interstitial colourless mineral. In some cases the irregularly-shaped relicts of the hypersthene are seen surrounded by small grains of hypersthene, which are of common optical orientation to the relicts; these in turn, are surrounded by augite grains associated with interstitial colourless mineral.

Each of the pseudomorphous aggregates mentioned above, is usually bordered by a narrow zone of augite.

The pseudomorphous aggregates after hypersthene sometimes contain small grains of spinel (0.1 mm. in diameter), in addition to the usual mineral grains described above. The spinel is usually green, often purple in colour, and sometimes colourless. Some grains are green or purple at their centres, but colourless at their margins. Myrmekitic intergrowth of the spinel and the recrystallized augite are sometimes seen (Pl. III, Fig. 4).

Plagioclase is often severely altered, especially when it, in company with the hypersthene, lies at the marginal portions of the grained masses. Around the crystal of the plagioclase, there often develops a kelyphite-like zone that is 1 mm. or more in thickness (Pl. III, Fig. 5), and this zone consists of small tabular crystals of albite, ill-shaped rectangular sections of which are arranged nearly perpendicular to the margin of the plagioclase crystal. The albite is of a dirty appearance, due to fine striations, and its refractive index $\alpha=1.526$. The kelyphite-like zone is sometimes quite thick, surrounding a small reilct of the original plagioclase. In some cases the plagioclase is completely replaced by a dirty fibrous aggregation of the albite crystals, especially when the original crystal was relatively small.

At the outermost portion of the pyroxene-plagioclase aggregate, and especially where the hypersthene and bytownite are severely attacked, there often develops a reaction zone with a thickness of 1.5 mm. or more (Pl. III, Fig. 6). The inner part of this zone consists mainly of ill-shaped crystals (about 0.8 by 0.2 mm.) of nepheline, the refractive indices of which are $\omega=1.548$, $\varepsilon=1.538$. The mineral is gelatinized by hydrochloric acid. The nepheline frequently encloses vermicular-formed colourless glass. The outer part of the zone consists of small augite rods and nepheline grains. In the texture, this part quite resembles the groundmass of the enclosing nepheline basalt, but lacking ore minerals.

Alteration Processes

The coarse-grained masses enclosed in the nepheline basalts show various evidences of thermal alterations in several of the minerals. From the fact that the hypersthene at the marginal portions of the inclusions was completely altered, while the accompanying augite was not, it is evident that the augite was stable, but the hypersthene was not, in the same thermal and chemical environment. From the fact that the hypersthene at the marginal portion of an inclusion was completely altered, while that in the interior of the same inclusion, remained almost unaltered, it is very probable that the chemical effect of the surrounding magma did not reach the interior portion of the inclusion at the same temperature. When a grained mass, a few cm. across, was enclosed in the nepheline basalt magma, the temperature difference between the margin and the interior of the inclusion was not significant.

The hypersthene crystal with a thin peripheral altered zone indicates that the crystal which was situated in the interior of the grained mass was only slightly affected by the catalytic agency from the magma, and that only the marginal portion of the crystal inverted into grains of monoclinic pyroxene ; these in turn inverted again into an orthorhombic form. In their laboratory experiments, Bowen and Scheirer have shown that intermediate members of natural enstatite-hypersthene series "experienced definite transformation only with the aid of a 'catalyst',"9) and that "a single crystal . . . was transformed into an aggregate of several grains of monoclinic pyroxene of random orienation with respect to each other and to the original orthorhombic substance."10)

The alteration product consisting of olivine grains and colourless mineral (devitrified glass?) seem to be the result of inversion of the hypersthene into monoclinic pyroxene and, in turn, the incongruent melting of the latter. This episode must have occurred at the temperature which prevailed in the nepheline basalt magma.

Formation of the augite grains from the hypersthene was the result of the reaction of the latter mineral with bytownite and, in part, with the surrounding magma ; in this reaction the hypersthene being furnished with lime and silica. The pseudomorph after hypersthene, consisting of grains of olivine and augite associated with the interstitial colourless mineral, shows that the supply of lime from outside was not sufficient.

Similar altered rhombic pyroxenes, with or without fragmental relicts of the original mineral, were somtimes reported 11) as phenocrysts of plagioclase basalts ; some of these apparent phenocrysts may be derived from the breaking up of such nodular inclusions as above stated.

The pseudomorphs after hypersthene usually have well-defined outforms of

9) N. L, Bowen and J. F. Schairer, Amer. Jour. Sci., 5 Ser. **29**, 167, 1935.
10) Idem, 169.
11) T. Tomita, Jour. Shanghai Sci. Inst., Sect. II, **1**, 3, 1933.
H. A. Powers, Amer. Jour. Sci., 5 Ser. **30**, 64–65, 1935.

the original crystals. If the alteration of the hypersthene had been completed in the depth before the outpouring of the magma, the aggregations of the altered products would have been much deformed, elongated, or disintegrated by the movement of the magma. It is very probable that the alteration occurred mainly immediately before the consolidation of the lava.

The spinel grains found in the large olivine crystals seem to be formed in the liquid from which the olivine was crystallized, however the vermicular spinel that it is intergrown with, or interstitial-filling among the recrystallized augite grains, seems to be due to the reaction of the hypersthene and the basic plagioclase that was thermally affected by the nepheline basalt magma. Vermicular spinel is found only in the masses that have both altered hypersthene and bytownite.

The kelyphite-like albite zone, found between the plagioclase and the altered hypersthene, can be formed by reaction of the plagioclase and the hypersthene. In chemical composition, a mixed melting of basic plagioclase and $MgSiO_3$ -rich hypersthene may closely resemble a certain mixture of the diopside-anorthite-albite system, worked out by Bowen.[12] From such melt, diopside and very soda-rich plagioclase can be formed; and according to circumstances, diopside may separate first and then simultaneous crystallizations of diopside and very soda-rich plagioclase may follow. In the present case, it is probable that the lime and silica necessary to convert the hypersthene into diopside were diffused from the bytownite, resulting in the formation of albite around the latter mineral. Small quantities of alumina and silica, released by this reaction, seem to have caused the albite to be dirty in appearance, and some to have entered into the diopsidic augite. As the formation of albite is frequently seen in the interior portions next to the outermost zone, the reaction may have been aided by catalytic substance from the surrounding magma; but the diffusion of the magmatic material into the inclusions seems to have been very limited. The temperature of the formation of the albite seems to have been not far from 1085°, the eutectic temperature of diopside and albite.

Formation of nepheline and augite, sometimes found in the outermost zone of the altered inclusions can be interpreted as the result of the reaction between the bytownite and hypersthene aided by the diffusion of substance from the surrounding magma. If an appropriate amount of soda is introduced from the magma, nepheline and augite may be formed from the bytownite and hypersthene by the following reaction:

$$\begin{matrix} 4(CaO.\ Al_2O_3.\ 2SiO_2) \\ Na_2O.\ Al_2O_3.\ 6SiO_2 \end{matrix} + 4(MgO.\ SiO_2) + 4Na_2O$$

$$= 5(Na_2O.\ Al_2O_3.\ 2SiO_2) + \begin{matrix} 4(MgO.\ SiO_2) \\ 4(CaO.\ SiO_2) \end{matrix}$$

Origin of Olivine-Nodules and Allied Grained Masses

Olivine-nodules and allied grained masses enclosed in nepheline basalts have

12) N. L. Bowen, Amer. Jour. Sci., 4 Ser. 40, 161–185, 1915.

been frequently reported from various parts of the world. They seem to have much in common. Especially, those reported from north Germany[13] are closely similar to ours in many respects.

As to the origin of these inclusions, some investigators consider them to be earlier segregations from the nepheline basalt magma, while others claim that the inclusions are foreign to the magma in which they were enclosed.

It is true that the minerals of the grained masses differ in their mineralogical character from the ordinary constituent minerals of the host rocks. The olivine-nodules, pyroxene-, and pyroxene-plagioclase-masses are linked with transitional types of the mineral associations. The grained masses can be seen to be genetically related to one another, and to have originated from a common original liquid that was unlike nepheline basalt magma. The grained masses are likely to represent various portions of heterogeneous grained rock body.

As to the origin of the grained inclusions, their mineral associations and the order of crystallization of the constituent minerals are significant as clues to the question of whether these inclusions owe their origin to the nepheline basalt magma or to other basic magma. Some twenty specimens observed do not cover the whole range of the mineral combinations of the grained masses.

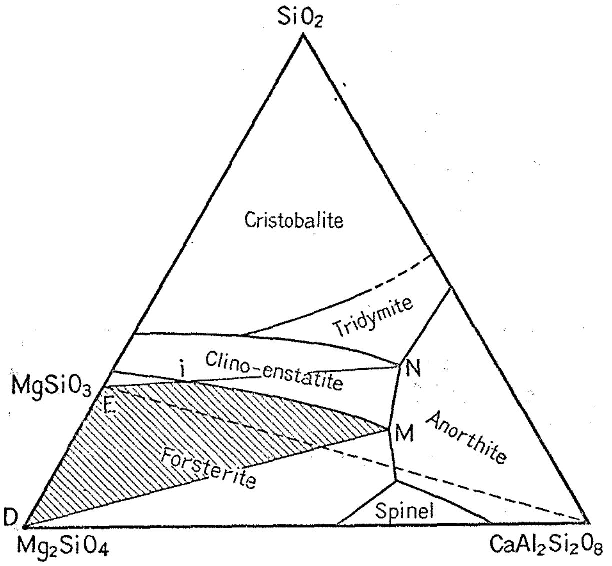

Fig. 2. Equilibrium diagram of the system, anorthite-forsterite-silica (after Andersen).

13) F. Rinne, Sitzungsber. Koenigl. preuss. Akad. Wiss. Berlin, **47**, 971–990, 1891.
R. Heinich, N. J. B.–B., **23**, 474–528, 1907.
Th. Ernst, Nachr. Ges. Wiss. Goettingen, Math.-Phys. Kl., N. F. **1**, 147–154, 1935.
Th. Ernst, Geol. Rundsch., **27**, 73–74, 1936.
Th. Ernst, Chemie der Erde, **10**, 631–666, 1936.

However, from the data obtained it is ovbious that, in some basic liquid, the olivine was the first mineral to separate, followed by the augite, then hypersthene and lastly the plagioclase, simultaneous crystallizations, in part, being provided.

The equlibrium diagram of the anorthite-forsterite-silica system, worked out by Andersen[14] and shown in Fig. 2, may afford a simple explanation of the formation of the mineral associations of the grained masses under consideration. From a certain mixture which lies within the forsterite field of the diagram, under suitable conditions, the following may result: (1) forsterite masses, (2) forsterite-clinoenstatite masses, and (3) clinoenstatite-anorthite masses. As Andersen[15] has pointed out, when small amounts of iron oxides, alkalies, and some minor constituents were added to the mixture above-mentioned, it can be considered that the crystallization course of the resulting mixture may not be changed in a large extent from that of the original mixture. From the mixture thus changed in composition, it is very probable that, under the favourable condition of crystal fractionation, some heterogneous rock may result from which the olivine-nodules, pyroxene-, and pyroxene-plagioclase-aggregates can be derived.

It may be concluded from the foregoing that the composition of the original magma from which the crystalline aggregates under consideration were derived, had close resmblance to a certain mixture within the forsterite field of the anorthite-forsterite-silica system, and presumably within the division DEiM of the diagram. The composition of such a mixture seems to be not far from that of some actual gabbro. The residual liquid, if any, from such magma can not be nepheline basalt magma.

Olivine-nodules and allied grained masses enclosed in nepheline basalts from different localities of the world often show quite similar petrographic characters. This can not be accidental. As Ernst[16] and others have pointed out, the olivine crystals with lamellar structure seem to indicate that they had been a part of a solid crust before they were introduced into the nepheline basalt magma. The grained masses are very likely to be detatched fragments from the wall rocks of the reservoir of the nepheline basalt magma. I can not agree with Ernst when he holds that the nodules are "Bruchstücke einer simatischen Schale der Erde."[17] I think that they were derived from a gabbroic magma. It is very probable that where the nepheline basalt magma has been, or nearby, there formerly had been a gabbroic magma. Seemingly there was some genetical relation between both magmas.

Phyllitic Xenoliths

Petrography

Xenoliths of phyllitic appearance are freqently found in the lava. They are usually irregular in shape and are variable in size, often attaining 10 cm. or

14) O. Andersen, Amer. Jour. Sci., 4 Ser. **39**, 407–454, 1915.
15) Idem, 453.
16) Th. Ernst, Chemie der Erde, **10**, 637, 1936.
17) Idem, 646.

more in diameter. The xenoliths consist of numerous thin layers which are dark brown, light gray, and sometimes green in colour; and not infrequently they are dark purplish, lithoidal in appearance. Irreguarly-shaped pores lined with zeolites are sometimes seen in the xenoliths. Surrounding the xenoliths, light green and somewhat coarser crystalline borders are usually developed.

The thin section shows distinct (A) outer and (B) inner reaction rims around (C) the main portion of the xenolith, the last-named being seen, when cut normal to the schistosity, to be composed of (i) lighter and (ii) darker layers (Pl. V, Fig. 1; Text Fig. 3). The xenoliths are sometimes penetrated by thin veinlets.

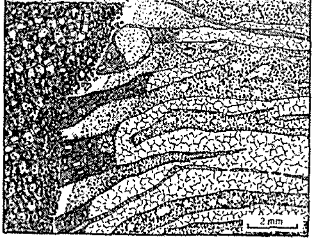

Fig. 3 Phyllitic xenolith (schematic). A: Outer reaction zone, B: Inner reaction zone, C: Main part, N: Nepheline basalt. (Confer Pl. V, Fig. 1.)

(A) The outer reaction zone is about 1 mm. thick, and consists of augite and glass. In appearance, this zone bears some resemblance to the groundmass of the surrounding lava; but the augite is rather coarsely crystallized, and ore minerals are usually lacking. The augite is well-formed and prismatic in habit, measuring 0.3 mm. at most in length. It is often twinned on 100, and is pale brownish green in colour. Its optical properties are: $\beta=1.695$, $\gamma=1.710$, $c\wedge Z=52°$, $2V(+)=59°$. The interstices of the augite crystals are filled with colourless glass ($n=1.488$). In the glass there are sometimes seen small pores that are lined with faintly double refractive mineral ($n\doteqdot1.487$, cristobalite?); and covering the latter mineral, prismatic crystals of phillipsite ($\gamma=1.5035$, $\alpha=1.4990$, positive elongation) are radially developed.

(B) The inner reaction zone is 2 to 4 mm. in thickness. Here the lighter and darker portions are distinguished, which are the extensions of the original phyllitic layers. The lighter portions consist of numerous crystals of sanidine, some of augite, and a considerable amount of brown glassy substance.

The sanidine is well-crystallized, and rectangular in sections, having the longer diameter of less than 1 mm. Swallow-tailed crystals are often found and the mosaic aggregates of anhedral crystals are not rare. The refractive indices are $\beta=1.5236$, $\gamma=1.5241$, and 2V is small.

The augite is of the same nature as that in the outer reaction zone, and is sometimes poikilitically enclosed in the sanidine. It, however, is noteworthy that where the augite crystal is in touch with the brown glassy substance in which the former is often embedded, the augite becomes deep green in colour and has a higher refractive index ($\alpha>1.710$) than the remaining colourless portion of the crystal. The optical orientations of both the green and colourless portions of one crystal are quite different, and in the green part $c\wedge X'=10°$, while in the colourless part $c\wedge Z'=37°$. Some crystals, embedded in the brown substance, are of an over-all uniformly deep green colour. It seems that the chemical composition of the growing portion of the augite crystal was affected by the sodium content probably of the brown substance, and formation of the aegirine resulted.

The brown substance occurring as interstitial fillings among the crystals of the sanidine and augite, is usually anisotropic and structureless, its refractive index being n = 1.575. Partly, however, radial fibrous structures are seen, the slender brown fibres showing strong double refraction (Ng = 1.587). This mineral is undeterminable.

The darker portions of the inner reaction zone are seen to be the extensions of the darker layers of the xenolith. The textures of these portions are extremely fine, and so it is difficult to determine the minerals. Hypersthene seems to be the main component.

(C) The main portion of the xenolith is phyllitic in texture, and consists of alternates of lighter and darker layers, each being about 0.5 to 1.0 mm. in thickness. Neither kind of the layers are always sharply defined; one is sometimes enclosed in the other as irregular patches and streaks.

(i) The lighter layers are colourless, or almost colourless, and show a sort of mesh-structure, being divided by a network of fine cracks. In polarized light, the colourless portions are proved to consist of angular or subangular grains of faintly double refractive mineral, and the cracks to be filled with colourless glass. The texture is partly spherulitic. The refractive indices of this unknown mineral are: Np = 1.503, Ng = 1.512. The refractive index of the glass is n = 1.530.

Well-shaped, clear orthoclase ($\beta = 1.5224$; $\gamma = 1.5246$; 2V, large) is often met with. The crystals are 0.4 mm. at most, in length, and are of rectangular or swallow-tailed forms in a section.

(ii) The dark layers have an uneven and varying appearance even in a single slice. Opaque or nearly opaque patches or streaks are irregularly distributed in dirty brown areas. Associations of thermal metamorphic minerals vary from place to place in a thin section. The almost opaque patches consist of dense aggregates of minute rounded grains of purplish spinel (0.005 mm. in diameter); and on account of the dark borders of the grains, due to the high index of refraction, the aggregates seem to be almost opaque. Surrounded by the aggregates of the spinel, various minerals are unevenly distributed, as follows: aggregates of several grains of corundum, about 0.1 mm. across, often associated with green corundphyllite; rare minute flakes of rutile, 0.05 by 0.01 mm. in size; very rare anatase (?); and swarms of sillimanite, in the form of fibrolite (0,05 mm. long). Mosaic aggregates of cordierite ($\gamma = 1.544$) are sometimes seen, inserted between the contorted brown layers.

As rare instances, minute flakes of pale brown biotite (0.05 mm. or less in diameter) with corroded outforms are found densely crowded with spinel grains, the former being seemingly scanty remnants of thermally altered mineral. Biotite formation of a very late stage is also seen in minute drusy pores that are lined with feldspar. Reddish to pale brown flakes of biotite (0.1 mm.) develop on the feldspar, and the interstices of the flakes are filled with zeolitic matter.

The brown areas of the darker layers consist mainly of isotropic material (n = 1.534). In some portions this material is seen to be an aggregate of well-defined minute crystals (about 0.3 mm. in diameter) that are square or hexagonal in sections; the mineral is undeterminable. Some portions of the brown areas are composed of feltic aggregates of ill-defined feldspathic laths, stained with dirty brown substance.

Alteration Processes

The darker layers of the xenoliths, which contain corundum, rutile, spinel, sillimanite, etc., can be taken as representative of the micaceous layers of the original rocks, and the lighter layers, as that of feldspathic or kaolinitic portions of the original xenoliths. In the Nagahama district the lava is partly underlaid by phyllites that consist essentially of sericite, albite, quartz, and ores. The texture of these phyllites closely resembles that of the xenoliths under consideration, though the component minerals of the latter have been thoroughly altered. The original rocks of the xenoliths are evidently the argillaceous phyllites and were derived from the underlying sediments.

The alteration minerals of the xenoliths described above are largely pyrometamorphic, the metamorphism being of typical sanidinite facies. The uneven distribution of the alteration minerals in the xenoliths indicates that molecular diffusion in the xenoliths was insignificant. From the alteration minerals, it can be recognized that permeatin of the material from the magma into the xenoliths was not significant, except in very limited portions of the xenoliths. Though the thermal alteration of the xenoliths is intense, the chemical interchange between the xenoliths and the enclosing magma is not considered to have been remarkable, i. e., the digestion of the xenolithic matter by the magma has been insignificant.

It cannot be considered that the xenoliths have occurred in a deep-seated reservoir and that they have been in a yielding state in the magma. They have been captured probably from rather shallow portions of the volcanic vent, and were not transported a long distance after the completion of the alteration processes. By raising the temperature, alteration of the xenoliths was accomplished, for the most part, immediately before the consolidation of the magma on the earth surface or nearby. Angularity of the xenolithic fragments and preservation of the phyllitic texture seem also to warrant the above considerations.

The nepheline basalt magma seems not to have experienced the contamination of the phyllitic xenoliths to any large degree.

Formation of Trachytic Veinlets in the Xenoliths

As rare instances the fine veinlets, 1 mm. in thickness, with a trachytic mineral composition are found in the xenoliths, sharply cutting the layers of the latter, and often shooting into branches (Pl. V, Fig. 2). They consist essentially of anorthoclase and augite with a subordinate amount of apatite and ilmenite. The crystals of the anorthoclase ($\alpha = 1,5253$; 2V, small) are about 0.5 mm. in length, and ill-shaped, showing rough, rectangular secitions. The augite is of pale green or nearly colourless, and only a few crystals of this mineral are found in the main portion of the veinlets, but minute rods (0.05 mm. long) of the mineral have accumulated thickly on the walls of the veinlets. Very rare small fragments of yellowish-brown to greenish-brown amphibole are met with. These veinlets are micro-syenitic or trachytic in mineral composition and in texture(Fig.4).

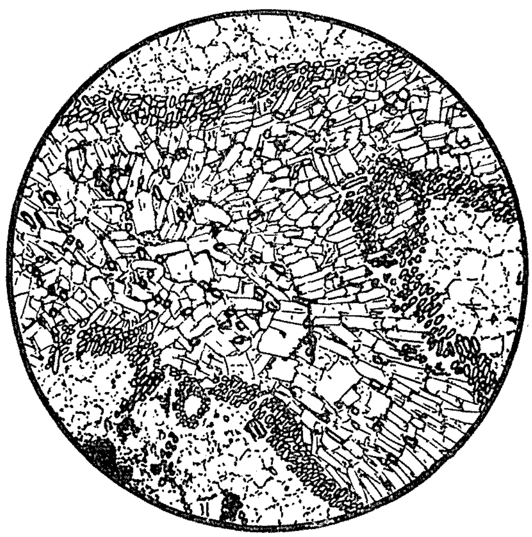

Fig. 4. Trachytic veinlet in phyllitic xenolith. ×34. (Confer Pl. V, Fig. 2.)

The trachytic veinlets in the xenoliths have outstanding features. The formation of these veinlets is evidently due to the injection of the surrounding nepheline basalt magma through the fissures of the xenoliths that were immersed in the magma, and were still in an unmelted state. By reaction with the fissure walls of the xenoliths, molecules of nepheline of the infiltrated magma have been converted into those of anorthoclase. Introduction of silica from the xenoliths into the magma is out of question.

The reaction zones along the peripheries of the xenoliths are also roughly trachytic in mineral composition as already described (though the glass may be somewhat silica-rich). Here, however, the feldspar is sanidine, instead of anorthoclase, because the recrystallized material of these zones presumably was mainly that of the xenoliths and the participation of the magmatic material was not great. Accumulation of augite crystals on the walls of the veinlets as well as along the outermost peripheries of the xeonliths may be interpreted in the same way as in the usual case of corona structure of quartz or feldspar xenocrysts of the ordinary basalts.

Summary

The melilite-bearing nepheline basalt which is of a new and unique occurrence in Japan is described.

The chemical composition of the rock is similar to the average melilite-nepheline basalt of the rest of the world.

The geological relation between the nepheline basalt, hitherto known, and the melilite-nepheline basalt, newly found, is not clear on account of the paucity of good exposures; but the latter type seems to be a local facies of the nepheline basalt flows.

The lava has locally numerous coarse-grained inclusions such as olivine-nodules, augite-hypersthene masses, and augite-hypersthene-bytownite aggregates. The component minerals of the grained masses show various grades of alteration. When the hypersthene and the augite were equally heated in the natural "laboratory" under the same conditions, the hypersthene was much altered while the augite only slightly melted.

The hypersthene seems to have been partially inverted into monoclinic pyroxene by raised temperature and again into a rhombic form by cooling.

The hypersthene was incongruently melted, resulting in the aggregates of olivine grains and glass.

Reaction between the hypersthene and bytownite resulted in the formation of albite and augite.

Reaction between the hypersthene and bytownite, aided by surrounding magma, resulted in the formation of nepheline and augite.

From the mineral associations of the grained inclusions and the order of separation of their constituent minerals, the chemical composition of the original liquid from which these minerals were derived is approximately assumed. The inclusions of the grained masses cannot be seen as earlier segregations from the enclosing nepheline basalt magma; it is very probable that they originated from a gabbro magma.

The nepheline basalt magma seems not to be merely a descendant of a gabbro magma; however, it is likely that where the nepheline basalt magma was born, there, or thereabouts, had been a gabbro magma. Between the nepheline basalt magma and the gabbro magma there seems to be a certain genetical relation.

In the lava, the xenoliths of altered argillaceous rock are frequent; the original rock of which is evidently the phyllite underlying the lava.

The argillaceous xenoliths show remarked pyrometamorphism. Chemical interchange between the phyllitic xenoliths and the enclosing magma seems to be very limited; thus assimilation of the phyllitic xenoliths by the nepheline basalt magma cannot be extensive.

The veinlets with trachytic composition in the xenoliths are formed from the nepheline basalt magma, being supplied with necessary silica by the phyllitic xenoliths.

This investigation was carried out with the aid of a grant from the Research Conference of National Arts and Sciences, and in part with an Education Ministry grant for natural science.

Explanation of Plates

Plate III.

Fig. 1. Melilite-nepheline basalt. Nepheline and augite, the former frequently moulds about the latter, and magnetite. Melilite with mid-rib, surrounded by dark rim (in the centre of the figure). ×75.

Fig. 2. Melilite-nepheline basalt, showing phenocryst of melilite (in the centre of the figure). ×85.

Fig. 3. Zoned phenocryst of melilite in melilite-nepheline basalt. Crossed nicols. ×140.

Fig. 4. Altered inclusion (augite-hypersthene-plagioclase mass) in nepheline basalt. Myrmekitic intergrowth of spinel (black) and augite (gray); plagioclase, white (lower, middle); pseudomorphs after hypersthene, gray, fine aggregates (on left, and right of the field). ×35.

Fig. 5. Altered inclusion (augite-hypersthene-plagioclase mass) in nepheline basalt. Shows pseudomorphs after hypersthene, consisting of olivine and augite grains with interstitial colourless matter, surrounded by narrow border of augite; plagioclase, light gray, cleaved (upper middle and lower right); and unaltered augite (upper right). ×35.

Fig. 6. Reaction zone of altered inclusion (augite-hypersthene-plagioclase mass) in nepheline basalt. Aggregate of nepheline crystals irregularly penetrated by vermicular glass, light gray (large area in centre and in lower right); unaltered augite, light gray (lower left); and fine aggregate of nepheline and augite, dark gray (upper and right margin). ×30.

Plate IV.

Fig. 1. Olvine-nodule in nepheline basalt. Shows granular olivine, light gray; with picotite, black. Darker fine-grained area on the right of the nodule is nepheline basalt. ×10.

Fig. 2. Olivine-nodule in nepheline basalt. Olivine (large three crystals), light gray; spinel enclosed in olivine, dark gray; and magnetite in olivine, black. Darker marginal portion is nepheline basalt. ×10.

Fig. 3. Augite-hypersthene mass in nepheline basalt. Augite, light and dark gray cleaved; altered hypersthene, very fine-grained aggregate (centre). Nepheline basalt is seen along the upper margin of the mass. ×10.

Fig. 4. Augite-hypersthene-plagioclase mass in nepheline basalt. Plagioclase, light gray; augite and hypersthene, dark gray finely cleaved. Nepheline basalt occupies the upper right area of the figure. ×10.

Plate V.

Fig. 1. Phyllitic xenolith in nepheline basalt. Alternate of the light and the dark layers represents the original texture of a phyllite. Along the left margin of the xenolith, narrow reaction borders are seen; and to the left of these, nepheline basalt is seen. ×10. (See text figure 3.)

Fig. 2. Phyllitic xenolith in nepheline basalt. Shows trachytic veinlet cutting the xenolith. ×10. (The circular area is represented in text figure 4.)

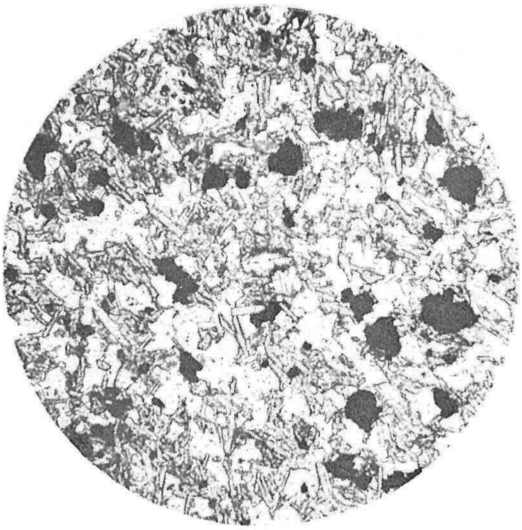

Fig. 1

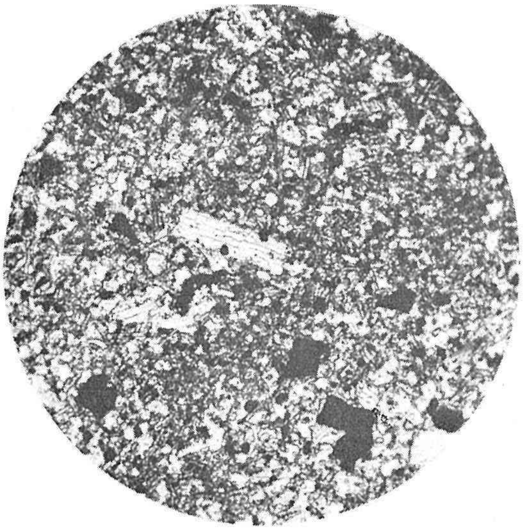

Fig. 2

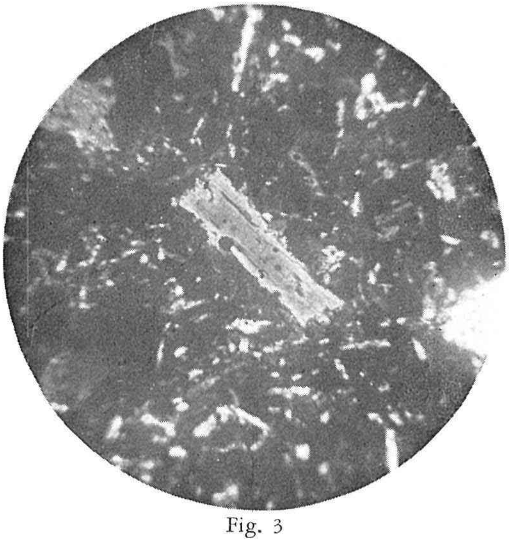

Fig. 3

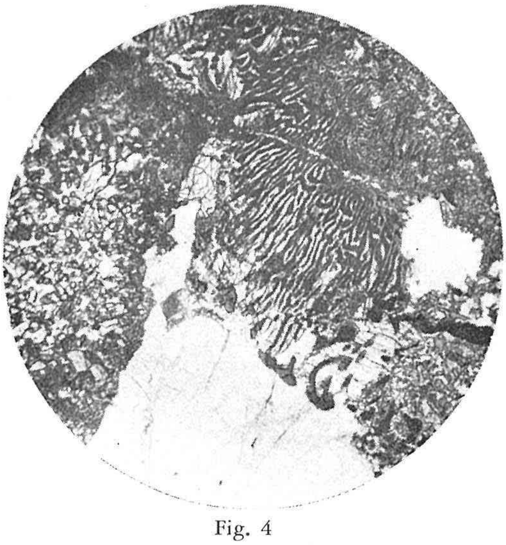

Fig. 4

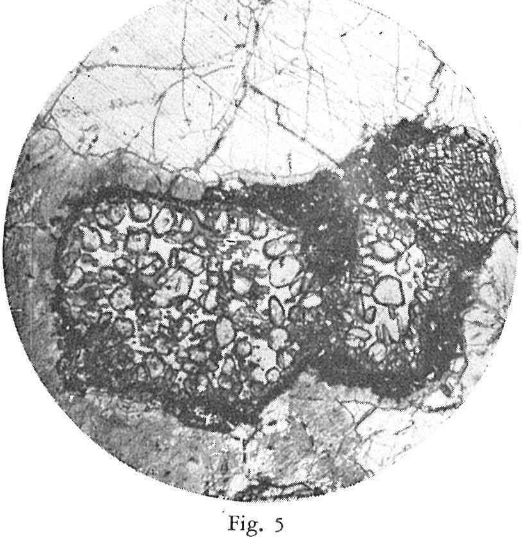

Fig. 5

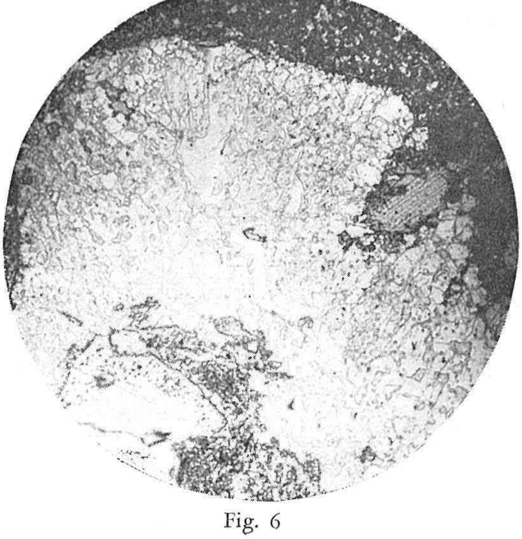

Fig. 6

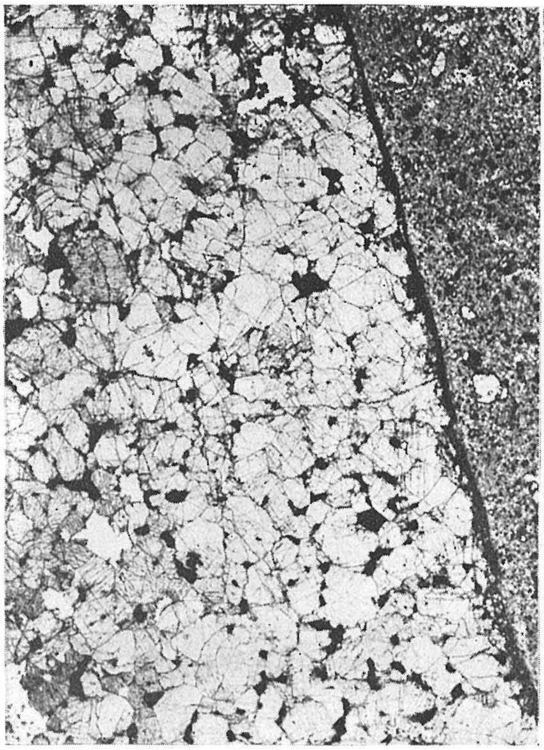

Fig. 1

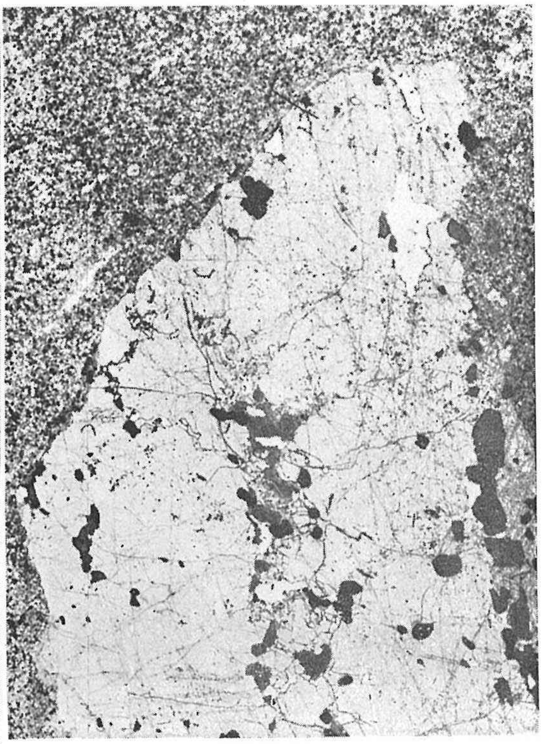

Fig. 2

Fig. 3

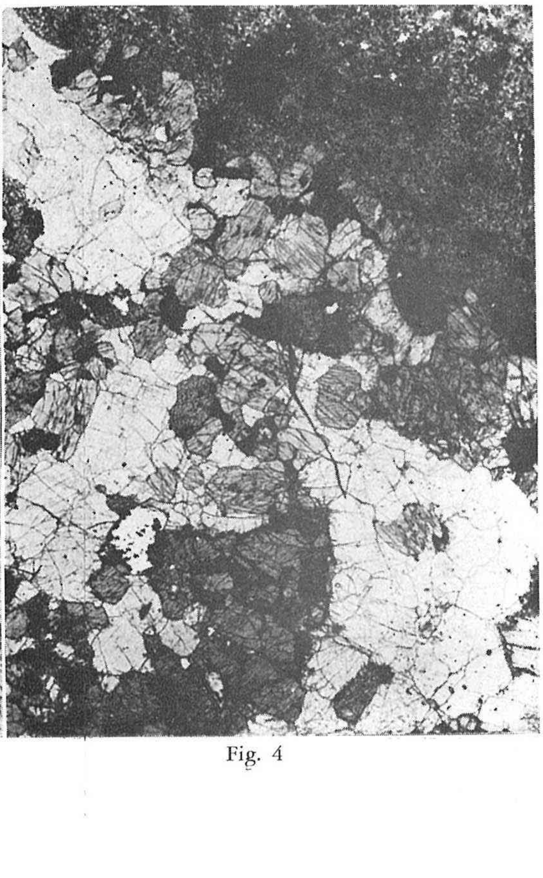

Fig. 4

Fig. 1

Fig. 2