Petrology. — *The association of alkali rocks and metamorphic limestone in a block ejected by the volcano Merapi (Java).* By H. A. BROUWER.

(Communicated at the meeting of October 27, 1945.)

In 1928 I have drawn attention to the production of alkali rocks from pyroxeneandesitic magma associated with limestone [1]). Zones of trachyte, leucitephonolite and leucite-bearing phanerites were observed in a large block (50 × 50 × 30 centimetres) of metamorphic limestone, which was found on the lahar field of the Kali Batang on the SW slope of the volcano Merapi. I have recommended further study of limestone xenoliths from Javanese volcanoes but the limestone block from the Merapi still seems to be the only described example of its kind and it may be of interest to give some more details about the composition of the samples, which are at my disposal.

Numerous smaller xenoliths of metamorphic limestone have been found enclosed in the lava of the dome and flows of the Merapi. These smaller xenoliths are not associated with alkali rocks [1]). In the investigated samples of the large block the typical Merapi lava is not found; an original shell of this lava may have been lost when the block came rushing down the slope with great rapidity in one of the avalanches, which are a characteristic feature of the activity of the volcano.

The Merapi magma.

The rock of the lava dome, which started to rise in the crater in 1883 and which was partly destroyed during the explosive eruption of 1930 is a pyroxeneandesite with phenocrysts of plagioclase and pyroxenes: in some samples amphibole, which mostly is strongly resorbed, is also present. The numerous plagioclase phenocrysts (labradorite and bytownite) have a zonal structure with frequent alternation of basic and more acid zones. The phenocrysts of hypersthene are far less numerous and smaller than those of augite. Larger crystals of iron ore are also found. The groundmass consists of plagioclase, pyroxene, iron ore, some apatite and a varying amount of glass.

The rocks of the young lava flows of the volcano show a similar mineralogical composition and the chemical analyses of the dome and flows, which are given in the following table, show their uniform chemical composition.

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[1]) H. A. BROUWER. Alkaline rocks of the volcano Merapi (Java) and the origin of these rocks. Proc. Kon. Akad. v. Wet. Amsterdam, 31, 1928, p. 492 and Production of trachyte and phonolite from pyroxeneandesitic magma associated with limestone. Journ. of Geol., 36, 1928, p. 545.

	I	II	III	IV
SiO_2	54.81	54.81	55.55	54.95
Al_2O_3	19.26	18.90	18.92	18.98
Fe_2O_3	4.85	5.56	4.63	5.40
FeO	2.94	2.49	2.84	2.23
MnO	0.21	0.17	0.20	0.17
MgO	2.53	2.70	2.41	2.49
CaO	8.48	8.60	8.43	8.60
Na_2O	3.70	3.58	3.62	3.62
K_2O	1.95	2.15	2.13	2.13
H_2O+	0.28	0.13	0.15	0.21
H_2O-	0.05	0.01	0.06	0.11
TiO_2	0.78	0.84	0.80	0.83
P_2O_5	0.32	0.34	0.31	0.38
Sum	100.16	100.28	100.05	100.10

I. Pyroxeneandesite, eastern part of lava dome, Merapi. Anal. P. J. DEN HAAN in M. NEUMANN VAN PADANG. Vulk. en Seism. Med. Dienst v. d. Mijnbouw in Ned. Indië, no. 12, 1933, p. 76.
II. Pyroxeneandesite, eastern part of lava dome, Merapi. Same reference as. I.
III. Pyroxeneandesite, lava flow of 1930. Same reference as I.
IV. Pyroxeneandesite, lava flow of 1931. Same reference as I.

The normative composition was calculated [1]) for II with the following result:

Q	6.54	
Or	12.79	
Ab	30.39	
An	28.91	
Di	9.29	*Andose*
Hy	2.45	II, "5, 3, 4
Mt	6.15	
Il	1.60	
Hm	1.36	
Ap	0.67	

The amount of normative quartz indicates that the glass is quaric. As alkali felspars were not observed amongst the constituents of the rock they may be concealed in the glass and in the plagioclase. In comparing

[1]) The normative compositions, which are mentioned in this publication, have been calculated by Dr. W. P. DE ROEVER.

the mode with the norm the modal composition of the soda-lime felspar leaves an amount of soda for alkali felspar.

In connection with the rather high potash content of the Merapi rocks it is of interest that rocks from other East Indian volcanoes, which have a similar chemical composition, are sometimes found associated with typical alkali rocks. Some chemical analyses are given for comparison in the following table.

	I	II	III	IV	V	VI
SiO_2	55.42	54.33	55.64	55.94	56.52	54.63
Al_2O_3	17.39	18.31	17.91	17·70	17.87	17.89
Fe_2O_3	1.56	3.01	3.19	2.76	3.69	5.73
FeO	6.82	4.41	5.13	4.74	1.91	3.40
MnO	0.71	0.17	0.14	0.13	0.17	0.15
MgO	3.28	3.65	3.20	3.50	4.18	3.19
CaO	7.57	8.41	7.16	7.60	6.61	7.82
Na_2O	2.41	3.04	3.65	3.66	3.72	3.25
K_2O	2.67	2.05	2.07	1.76	2.25	2.07
H_2O+	0.17	1.24	0.62	0.44	1.90	0.67
H_2O-		0.36	0.45	0.28	0.71	0.17
TiO_2	1.07	0.71	0.93	1.40	0.49	0.82
P_2O_5	0.58	0.13	0.15	0.28	0.22	0.17
Sum	99.98 [1])	99.82	100.24	100.19	100.24	100.04 [1])

I. Shoshonite, Mt Bromo, Java. Anal. E. W. MORLEY in J. P. IDDINGS and E. W. MORLEY. Journ. of Geol., 23, 1915, p. 233 (with O.11 Cl, 0.03 F, 0.03 S, 0.13 BaO, 0.03 SrO).

II. Andesite (with augite, hyperstene, hornblende and olivine), Mt. Loeroes, Java. Anal. R. DJOKOJOEWONO in R. W. VAN BEMMELEN, Nat. Tijdschr. Ned. Indië, XCVIII, 1938, p. 194.

III. Pyroxeneandesite, Mt. Pangonan, Dieng Mts, Java. Anal. R. DJOKOJOEWONO in R. W. VAN BEMMELEN, Ingenieur Ned. Indië, 4, IV, 1937, p. 134.

IV. Hypersteneandesite, Mt Slamat, Java. Anal. R. G. REIBER in Jaarb. Mijnw. Ned. Indië, 59, Alg. Ged. 1930, p. 2.

V. Basalt (acid, with some hornblende, without olivine), Mt Penanggoengan, Java. Anal. C. KOOMANS in PH. H. KUENEN, Leidsche Geol. Med. 7, 1935, p. 283.

VI. Andesite to trachyandesite, Mt Soromandi, Soembawa. Anal. H. W. V. WILLEMS in H. A. BROUWER. Versl. Ned. Akad. v. Wet. 52, 1943, p. 304 (with 0.08 SrO).

The andesite of Mt Loeroes, Java (analysis II) is associated with leucitebasanites; the andesite to trachyandesite of Mt Soromaṇdi, Soembawa (analysis VI) is associated with different leucite-bearing lavas and the association of the pyroxeneandesite of the Merapi with alkali rocks is shown by the local occurrence of these rocks in limestone.

[1]) With the additions mentioned below.

With regard to the composition of the glass base in the Merapi rocks the analyses [1]) of a glass-rich pyroxeneandesite and its glass base (I and II in the following table) are of particular interest. The rock was collected in 1876 and may have been thrown out during the strongly explosive eruption of 1872.

	I	II	III
SiO_2	57.76	65.05	53.95
Al_2O_3	18.39	17.60	27.45
Fe_2O_3	7.51	3.10	1.09
CaO	6.21	3.58	11.48
MgO	3.34	1.05	trace
Na_2O	3.63	3.54	4.51
K_2O	2.61	4.16	0.79
H_2O [2])	0.94	1.56	0.48
Sum	100.89	99.64	99.75

I. Pyroxeneandesite (vitroandesite), Mt Merapi, Java. Anal. A. LAGORIO, Tscherm. Min. u. Petr. Mitt., 8, 1887, p. 467.
II. Glass base in I. Same reference as I.
III. Plagioclase phenocrysts in I. Same reference as I.

The plagioclase phenocrysts (III) have about the composition Ab_3 An_4 and contain about 4.5 % Or. A comparison of the analyses I and II shows that the residual liquid was richer in silica and potash and poorer in iron, lime and magnesia. The calculation of the normative composition of the glass base gives about 20 % Q, 25 % Or, 30 % Ab and 18 % An and shows that the glass is strongly oversaturated and conceals much felspar, especially potash-rich felspar, which was not found by microscopical investigation. Although enriched in potash, the residual liquid would need strong desilication before it could have crystallized to the leucite-bearing mineral assemblages, which are found in the ejected limestone block.

The metamorphic limestone.

The block of metamorphic limestone has been described as a greyish green "schist" interlarded with small lenticles and strings of limestone. The limestone of the lenticles is altered by contactmetamorphism and partly consists of a chalky lime powder [3]).

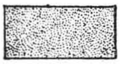
[1]) A. LAGORIO. Über die Natur der Glasbasis, sowie der Kristallisationsvorgänge im eruptiven Magma. Tsch. Min. u. Petr. Mitt., 8, 1887, p. 467.

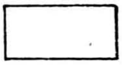
[2]) Loss on ignition.

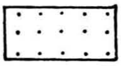
[3]) G. L. L. KEMMERLING. De hernieuwde werking van den vulkaan G. Merapi (Midden-Java) van begin Augustus 1920 tot en met einde Februari 1921. Vulk. Meded. Dienst van het Mijnw. in Ned. Oost-Indië, No. 3, 1921, p. 29.

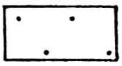
REFERENCES.

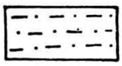
Principal minerals of the assemblages in figures 1—7.

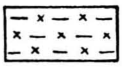
 limestone.

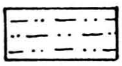
 wollastonite (locally gehlenite, pyrrhotite).

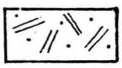
 wollastonite, augite.

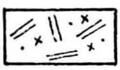
 gehlenite, augite, garnet, wollastonite.

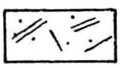
 plagioclase, augite (often with titanite).

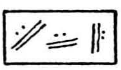
 plagioclase, biotite.

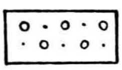
 plagioclase, wollastonite, augite.

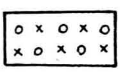
 potash-rich felspar, augite.

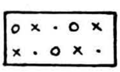
 potash-rich felspar, augite, biotite.

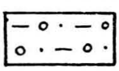
 potash-rich felspar, plagioclase, augite.

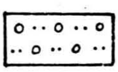
 potash-rich felspar, wollastonite, augite.

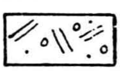
 leucite, augite.

 leucite, biotite.

 leucite, biotite, augite.

 leucite, plagioclase, augite.

 leucite, augite, wollastonite.

 leucite, potash-rich felspar, augite.

 glass-bearing parts (mainly leucitephonolite and trachyte to trachyandesite).

 calcite veins.

The figures 1—7, which are all six times enlarged, are sketches illustrating the composition of the investigated samples.

Figs. 1 and 2.

These figures show the transformation of the limestone into wollastonite and gehlenite and the formation of plagioclase- and leucite-bearing mineral assemblages.

The wollastonite-rich mineral assemblages are connected by transitions

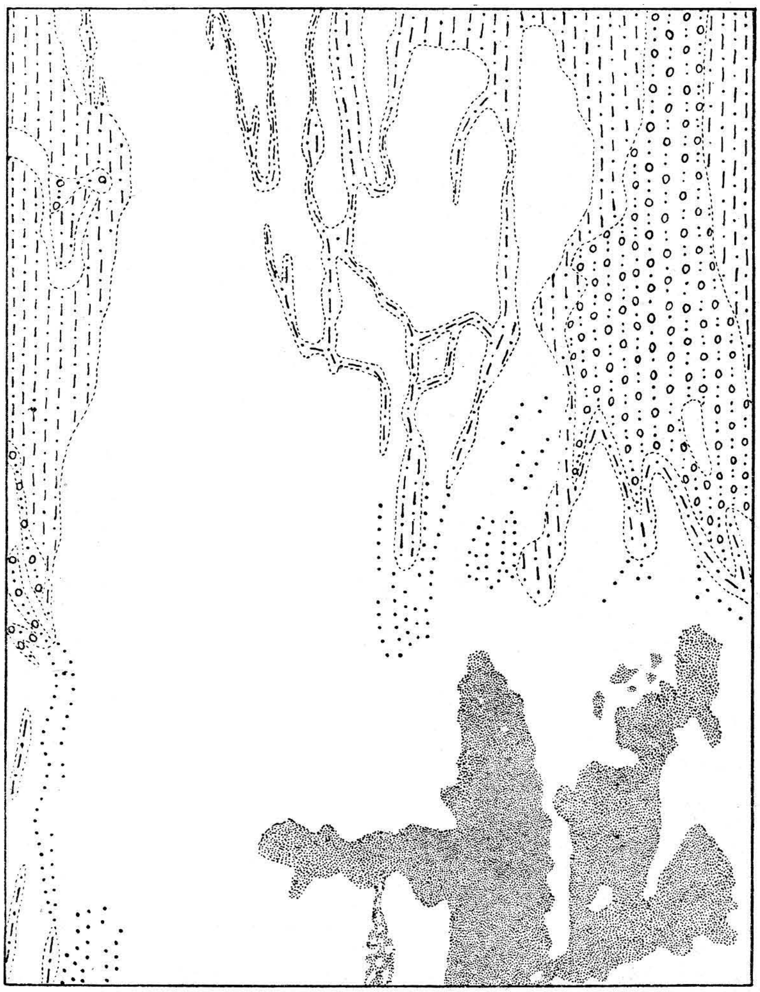


Fig. 1. Enl. × 6.

to those which mainly consist of plagioclase and augite and to those which mainly consist of leucite and augite. In the figures the following assemblages are distinguished: wollastonite-augite, plagioclase-wollastonite-augite, plagioclase-augite, leucite-wollastonite-augite and leucite-augite[1].

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[1]) The colourless mineral, which generally shows distinct optical anomalies, is always

Microscopically the limestone shows slight recrystallization and where the transformation into lime silicates is starting its colour changes in narrow zones and spots to dark grey, brown or black (fig. 8).

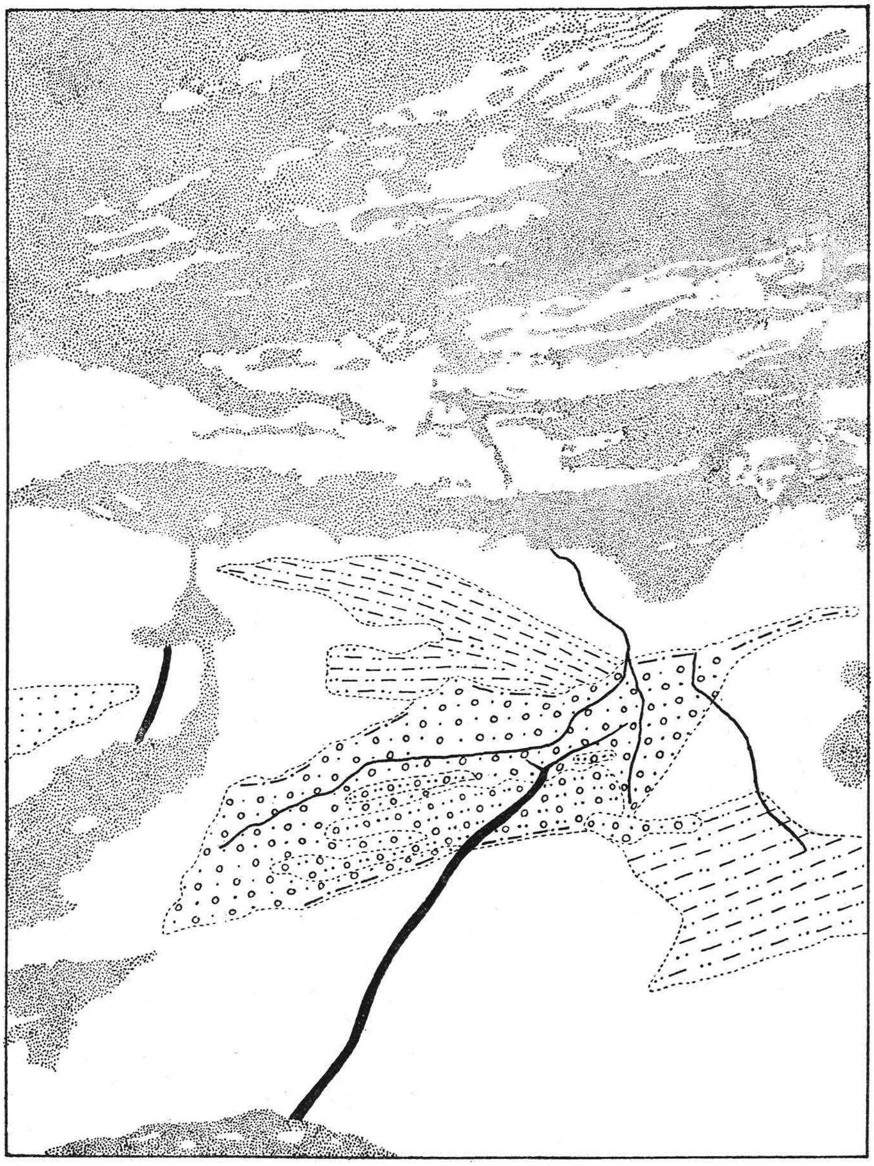

Fig. 2. Enl. × 6.

In the wollastonite-rich assemblages the crystals of this mineral may attain a length of 0.6 mm and the larger crystals are enveloped in a fine-

mentioned in this publication as leucite. Several microchemical tests and measurements of the refractive index confirm this determination; it is however possible that analcime (or potash analcime) is not absent in the investigated samples.

grained mixture of wollastonite and gehlenite with a grain size of about 0.03—0.06 mm. The small crystals of gehlenite accumulate locally in spots and bands, which sometimes border upon the plagioclase-bearing mineral assemblages. Other constituents of the wollastonite-rich assemblages are pyrrhotite, of which the size reaches up to 0.2 mm, and minute, mostly irregular, crystals, which resemble titanite and perowskite.

The other assemblages all contain augite, which appears in varied shades of green and brown, passing into greyish and purplish grey tints. The augite sometimes shows a purplish grey core with a narrow greenish to brownish grey margin. The crystals are often anhedral, their size may reach up to 0.4 mm, it varies gradually and very small grains (0.003—0.03 mm) are frequently found. The plagioclase in the plagioclase-augite and plagioclase-wollastonite-augite assemblages is up to about 2 mm in length (fig. 11), the crystals mostly are of rather large size except in the left upper part of fig. 1 where the grain size of the major part is about 0.01—0.03 mm and larger crystals, which reach up to 0.2 mm, are seldom found. The plagioclase is mostly very basic (bytownite to anorthite), a zonal structure with a rim of more acid plagioclase was observed in some crystals. For the greater part the crystals are anhedral, they enclose other constituents of the assemblages, especially augite, and they contain numerous minute inclusions of liquid or gas. The leucite forms a base, in which augite or augite and wollastonite are embedded; it shows distinct optical anomalies with polysynthetic twins. Other constituents of minor importance are pyrrhotite, titanite and calcite. The occurrence of calcite in narrow veins is shown in fig. 2.

Fig. 3.

A cross-section of a part of the metamorphic margin of a limestone lenticle is seen in the left lower corner of the figure. Wollastonite-rich assemblages are shown in the right half and in the left upper corner. The mineral assemblages in the main part of the figure vary strongly in mineralogical composition and grain size. All the glass-bearing parts, although showing important differences, are indicated by the same signature.

The limestone of the lenticle passes outward into a zone with a thickness of some millimetres, which for the greater part consists of lime sillicates: in the inner part mostly wollastonite and farther outward mostly gehlenite. A small part of this zone appears in the left lower part of the figure. It is surrounded by a zone in which the chief minerals are gehlenite, augite, wollastonite and garnet. Calcite, pyrrhotite, magnetite and small grains, resembling titanite and perowskite, are also found. In this zone the gehlenite crystals are partly of larger size, they reach up to 1.5 mm in diameter. The maximum size of the wollastonite is 0.2 mm. The mostly greenish augite may attain a length of nearly 1 mm. Some crystals of augite have a purplish core, which has the same crystallographic orientation and seems to be the remnant of an originally larger crystal, which has been replaced by the greenish augite. Intergrowth textures, e.g. of light yellow garnet and

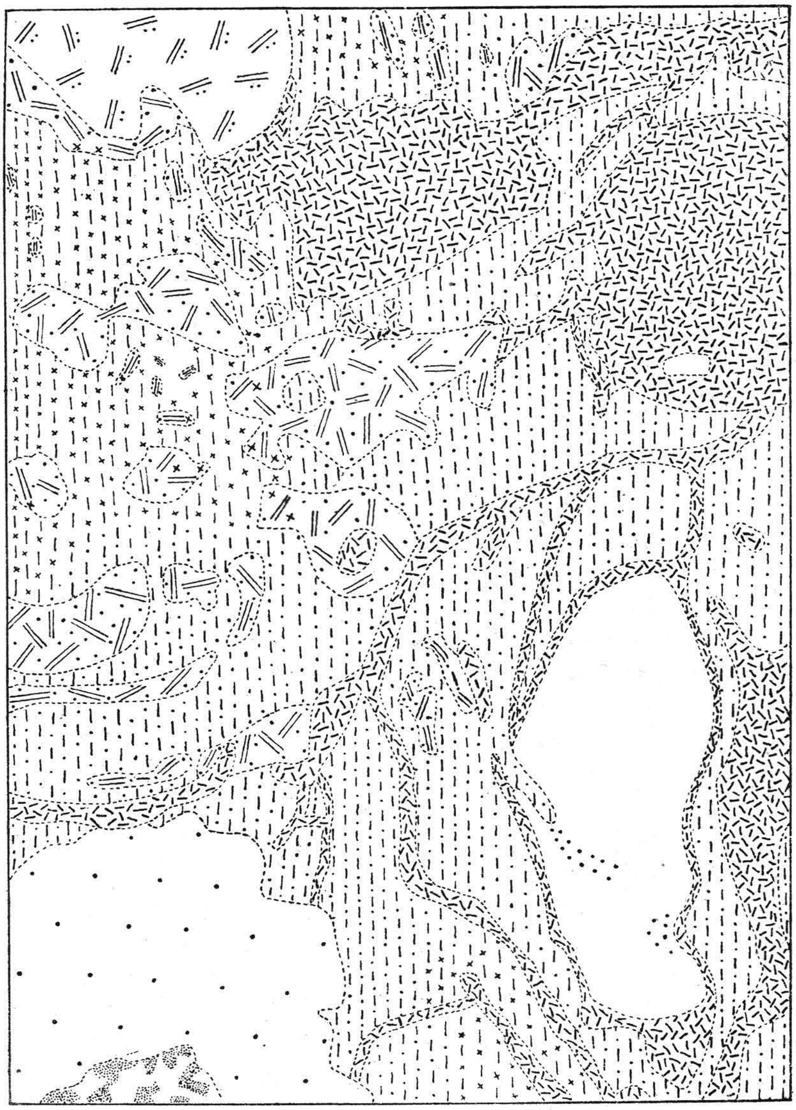

Fig. 3. Enl. × 6.

greenish to brownish grey augite, and poikiloblastic textures are a common feature. Characteristic is also the more or less distinct radiate arrangement in protruding sectors of the outer zone, which indicates a divergent streaming out of substance towards the contact. This outward movement is also illustrated by crystals of purplish augite, which partly lie outside the lime silicate zone and of which the part within this zone is partly transformed into greenish augite. At the contact the lime silicate zone is often rich in calcite and sometimes calcite and greenish augite are the only constituents (fig. 9). Other thin sections of the marginal part of the same limestone lenticle show that the character of the lime silicate zones changes from point to point. One section for instance shows a 2—3 mm thick wollastonite-rich inner zone, which is followed outward by a 0.2—0.5 mm thick wollastonite-gehlenite zone and a 0.05—0.75 mm thick outer zone consisting of calcite and augite.

The wollastonite-rich assemblages in the right half of the figure consist almost entirely of this mineral; the crystals reach a length of 0.5 mm but generally they are much smaller (about 0.1 mm). Augite is found locally, it is light-coloured with a greenish grey tint and larger crystal skeletons reach up to 1.5 mm in size. Calcite is found especially in the marginal parts, where the wollastonite borders upon a glass-rich zone. In the wollastonite-rich assemblage in the left upper corner of the figure the skeletons of augite, which often consist of isolated parts, attain dimensions up to 2 mm. The small crystals of potash-rich felspar are up to 0.12 mm in diameter. Calcite and some rare grains resembling titanite are also found. The two last mentioned wollastonite-rich assemblages have been attacked and imbibed by the surrounding substances and there are no indications that the line of contact moved outward. An outward movement seems to be connected with the presence of a core of limestone in the lime silicate assemblages.

The other assemblages in the figure — as far as they do not belong to the glass-bearing varieties — are microcrystalline to fine grained mixtures in which different felspars, augite and biotite are the main constituents. They often are vesicular, the vesicles are empty or they contain calcite. In the larger and smaller spots, which are indicated schematically in the left part of the figure, the principal minerals are potash-rich felspar and light greenish to light brownish grey augite (fig. 13). The smallest spots are not shown in the figure. Biotite is found in some of the spots but only where the surrounding mineral assemblage also contains biotite. It is strongly pleochroic from very dark brown to light yellow. The grain size is up to 0.5 mm for potash-rich felspar, up to 0.6 mm for augite and up to 0.1 mm for biotite. Other constituents which are sometimes found are pyrrhotite, titanite and calcite. An interstitional glass-bearing substance is sometimes found locally. The spots lie in a mixture with a much smaller grain size in which basic plagioclase is the main constituent, while brown biotite is abundant in one part and absent in the other. The biotite and most of the plagioclase reach up to about 0.05 mm in size. Pyrrhotite, magnetite and minute grains of augite and iron ore are also found. A colourless residual cement is present in varying amount. If birefrigent the refractive index points to potash-rich felspar; the cement may partly consist of leucite. In another thin section made of the same rock fragment at a distance of two centimetres from the described section, anhedral leucite is found as an important constituent of cement and spots. The biotite-free part is characterized by the presence of somewhat larger crystals of titanite and grey to greenish or purplish grey augite, which may attain a diameter of 0.1 mm and 0.25 mm respectively. In some parts of the plagioclase-augite assemblage, which are not shown by a separate signature in the figure, the grain size of the plagioclase is larger, reaching up to 0.2 mm. In these parts potash-rich felspar is sometimes found. Two spots, in which both felspars have a grain size up to about 0.1 mm, are shown in the figure. As to the shape of the crystals it is clear that biotite and plagioclase have been able to develop the best crystal boundaries. Euhedral crystals of biotite are numerous and the shape of the plagioclase is often rectangular. They have hindered the growth of crystals of potash-rich felspar and augite and they are found enclosed in larger crystals of the last mentioned minerals. In the spots, where augite and potash-rich felspar have developed under circumstances of comparative freedom, the augite may partly exhibit good crystal boundaries.

The glass-bearing parts of the rock show a great variety as to their glass content and the size and shape of the mineral constituents. There are transitions between these parts and the microcrystalline mixtures and then the boundary lines in the figure are approximate. The glass-bearing assemblages are strongly vesicular, the vesicles are empty or they contain calcite. In the more or less rounded parts in the upper part of the figure the vesicles, which mostly are empty, take up much of the space (fig. 10). The remaining part contains about equal quantities of a light coloured greenish augite and a brownish to colourless glass, which is slightly devitrified and contains some lath-shaped microlites of potash-rich felspar with a length of about 0.06 mm. Large skeletons of augite reach up to 1.5 mm in size, they often consist of isolated parts with simultaneous extinction. Smaller, often euhedral, crystals of augite with a size of 0.05—0.1 mm are also found. Near the margin of these glass-rich parts a zone, which is developed locally, contains small lath-shaped crystals of basic plagioclase, which partly have acid rims. This zone forms a transition to the adjacent plagioclase-rich mineral assemblage. The narrow zone which surrounds the wollastonite rock in the right lower part and the small oval spot in the centre of the figure show a similar character.

The zone to the right of the wollastonite rock in the right lower part of the figure is also strongly vesicular. It is much poorer in augite of which the crystals reach up to 0.25 mm in size. The microlites in the brownish glass are more numerous, they mostly consist of potash-rich felspar in which a core of basic plagioclase with extinction angles up to 37° is often found. Some plagioclase is also found in separate microlites and their number increases in a marginal zone, which is developed locally.

The other glass-bearing parts all form narrow bifurcating zones or veins in which the amount of glass is much smaller. They contain numerous vesicles, which sometimes take up more than half of the space, and mostly are empty. Microlites of potash-rich felspar, often with a core of basic plagioclase, are numerous. The average size of the microlites is about

0.05 mm, the diameter of the cores of plagioclase is rarely more than 0.01 mm. Minute crystals of light greenish augite and iron ore are found in the interstitional glassy substance, while a brownish mineral, which was rarely observed, resembles the kataphoritic amphibole of the leucite-bearing zones, which are found in other parts of the rock (p. 182). Phenocrysts are mostly absent. Numerous lath-shaped phenocrysts of potash-rich felspar with a length up to 1 mm were observed in one place in the left lower part of the figure. They enclose small plagioclase and augite crystals. Titanite and larger augite crystals are also sometimes found. As the potash-rich felspar, this augite has developed under circumstances of comparitive freedom and has been able to develop better crystal boundaries if compared with those of the adjacent plaglioclase-augite assemblage. The transition between the glass-bearing zone and the adjacent mineral assemblages is particularly clear where crystals of augite or titanite are partly or entirely enclosed in the glass-bearing zone and where this zone contains separate lath-shaped crystals of plagioclase.

The general features shown by the different mineral assemblages are the remarkable variability of grain size and mineralogical composition and the abundance of vesicles in the assemblages found between the parts of the rock, which are rich in wollastonite. Wollastonite must have occupied much of the space where these assemblages are now found and it has been attacked and replaced by magmatic substances which were rich in volatile constituents.

Fig. 4.

This figure shows the arrangement in more or less parallel zones of different mineral assemblages. Limestone appears in the lower part and a partly altered crystal of garnet is seen in the central part of the figure. The wollastonite-rich assemblage contains pyrrhotite and gehlenite. The crystals of wollastonite reach a size up to 1 mm but smaller grains with an average size of about 0.1 mm are numerous. Pyrrhotite mostly forms irregular crystals, which are up to 0.1 mm in diameter. Gehlenite is found in crystals, which reach up to 0.25 mm in size; it is found locally and is for instance lacking in the right middle part of the figure. A gehlenite-rich zone is found along a part of the lower boundary of the plagioclase-augite-leucite assemblage in the left lower part of the figure.

The garnet of which one crystal occurs in the central part of the figure is a nearly colourless light pink grossularite. One larger and two smaller separate parts of the original crystal are nearly entirely surrounded by a rim in which small crystals of a light brown garnet are found in wollastonite. The size of the small garnet crystals varies between 0.005 and 0.1 mm, it mostly is about 0.03 mm. These crystals, which are roughly shown in the figure, are also found scattered outside the rim but are never found in the adjacent plagioclase-bearing zones. This illustrates a certain amount of diffusion and the non-compatibility of grossularite with the approaching plagioclase-augite-leucite assemblage.

The other assemblages are partly connected by transitions, which could not all be shown in the figure. This counts especially for the plagioclase-

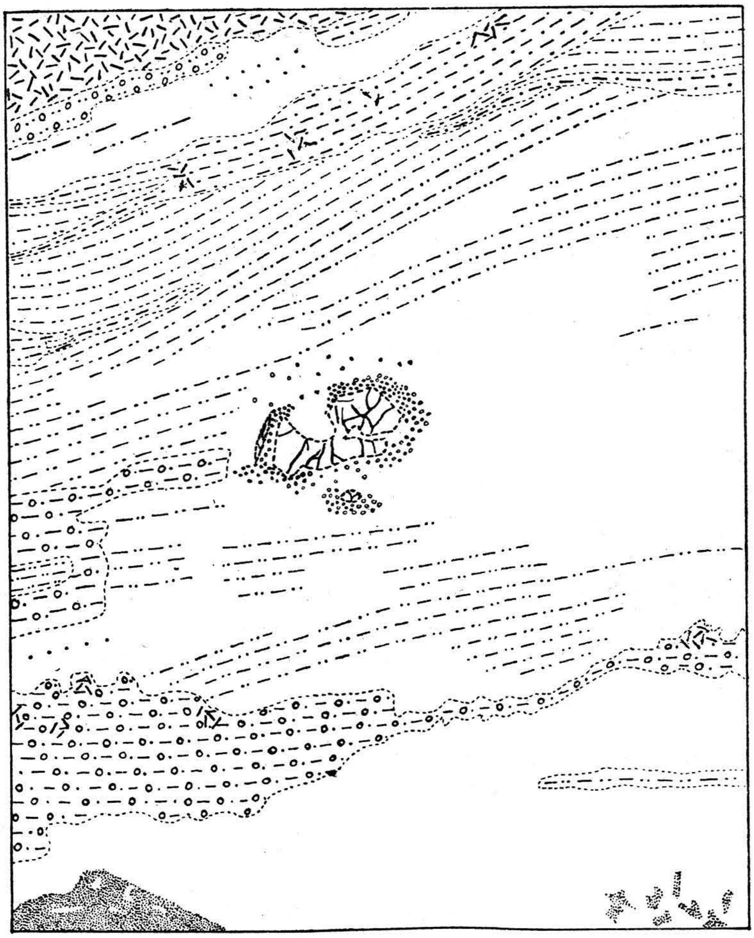

Fig. 4. Enl. × 6.
A partly altered crystal of grossularite in the centre of the figure.

augite assemblages with and without wollastonite and the wollastonite-augite assemblages with and without plagioclase.

In the zones or bands in which plagioclase is found with wollastonite and augite, the plagioclase, which has the composition of bytownite to bytownite-anorthite, is often elongated in the direction of the parallel structure. Crystals with a length of 1.5 mm and measuring only 0.15 mm across have been observed, they do not show good crystal boundaries and are crowded with inclusions consisting of the two other minerals of the assemblage, augite and wollastonite. A moderate amount of inclusions of liquid or gas is also found. The augite appears in various shades of greenish, brownish and purplish grey tints; it is up to 0.2 mm in diameter but the crystals are mostly much smaller and reach down to about 0.005 mm in size.

The zone in which plagioclase and augite are the main constituents locally contains interstitional glass-bearing spots with microlites of potash-rich felspar. Calcite, pyrrhotite and titanite are also found. The size of the plagioclase, which is very basic, ranges up from about 0.02 mm in fine grained parts to 0.5 mm in crystals, which are crowded with inclusions. The augite also varies much in size; skeletons of this mineral reach up to 0.8 mm in diameter. The crystals of plagioclase partly show a zonal structure with more acid rims. Near the glass-bearing spots they are often partly surrounded by potash-rich felspar.

Of the leucite-bearing assemblages, in which plagioclase and augite are the principal minerals, that to the left of the garnet crystal shows the coarsest grain. Plagioclase crystals up to 2 mm in size have been observed while the size of the largest crystal in the lower part of the figure is 1 mm. The plagioclase is bytownite to bytownite-anorthite with up to 93 % An, sometimes with a narrow more acid rim. Oscillatory zoning was observed in some crystals. Near the glass-bearing parts, which are found locally, the plagioclase is often partly surrounded by potash-rich felspar, which also forms microlites in these glass-bearing parts. The augite, which shows various shades of greenish, brownish and purplish grey tints, reaches up to 0.4 mm in size but generally the size is much smaller. Many augite crystals are enclosed in plagioclase. The leucite shows optical anomalies, crystal faces are absent and it encloses numerous crystals of augite. Its growth has been hindered by the plagioclase, which often shows good crystal boundaries where it borders upon leucite. Other constituents of the assemblage are titanite and interstitional calcite; the titanite is partly more or less idiomorphic and reaches up to 0.1 mm in size. Pyrrhotite and magnetite, both up to 0.1 mm in diameter, are rarely found. Wollastonite occurs enclosed in plagioclase and also in leucite, it partly forms needle-shaped crystals, which often show a radiate arrangement.

The narrow zone, which borders upon the zone of trachyte in the upper left corner of the figure, mainly consists of leucite and augite. The diameter of the leucite is up to 0.5 mm, it encloses numerous crystals of augite and some small crystals of titanite. Calcite is found in spots and small veins. The adjacent trachyte is strongly vesicular; it contains phenocrysts of potash-rich felspar, which are up to 0.4 mm in length. The glass-bearing groundmass contains numerous lath-shaped crystals and small microlites of potash-rich felspar, which reach up to 0.15 mm in length, and small crystals of an amphibole with affinities to katophorite of which the size does not exceed 0.05 mm.

From the above description it is evident that a stage of metamorphism during which the limestone was altered into wollastonite and garnet was followed by a stage during which the plagioclase-, augite- and leucite-bearing assemblages were formed in more or less parallel zones. This stage was interrupted when the limestone block was ejected and the still liquid part of the magmatic substances consolidated as glass.

Fig. 5.

The main part of the figure shows a wollastonite-rock in which various mineral assemblages are found in more or less parallel zones. A parallel structure is also more or less distinctly shown in the greater part of the plagioclase-augite zones, especially in the left half of the figure where the signature is parallel to the structure. Bifurcating zones of trachytic and leucitephonolitic composition are partly parallel and partly oblique to the main structure. Limestone appears in the left lower corner of the figure.

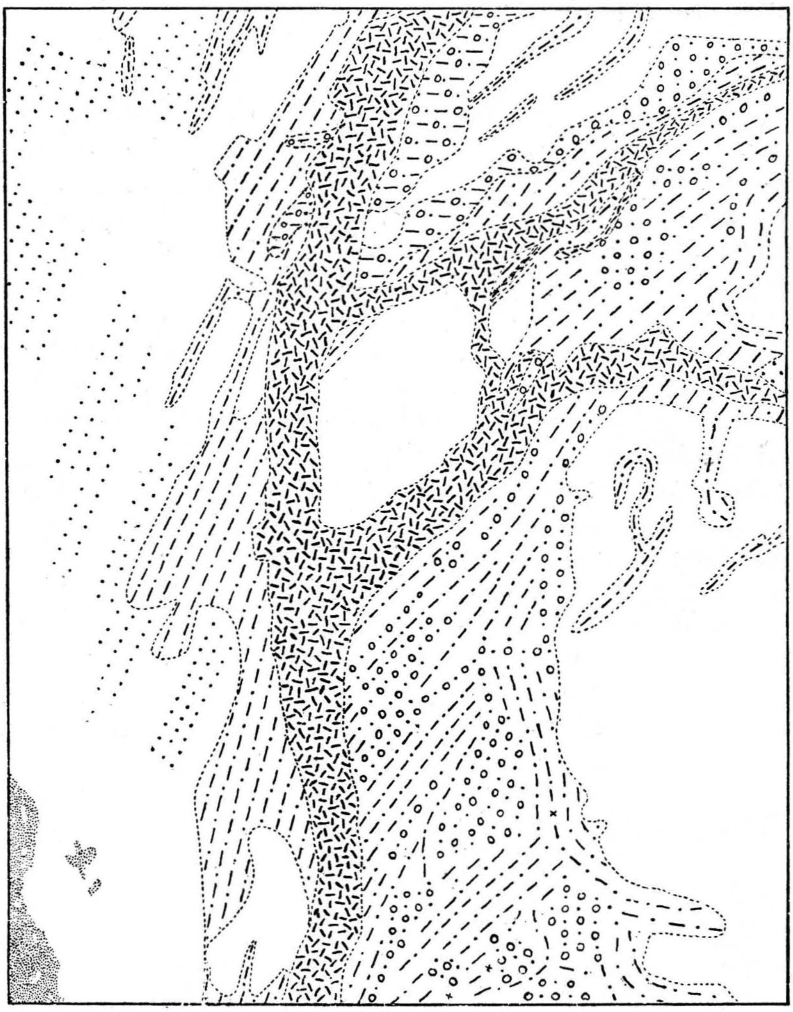

Fig. 5. Enl. × 6.

The wollastonite-rich parts consist nearly entirely of this mineral, it reaches up to 1 mm in size but the crystals are mostly much smaller (about 0.1—0.2 mm). Pyrrhotite and magnetite are both present in subordinate amount. Gehlenite has not been observed. The crystals of augite, which are arranged in more or less parallel zones in the wollastonite-rich parts, are up to 0.2 mm in size. Their colour varies often in the same crystal from greyish brown to nearly colourless or light greyish brown; greyish green tints have also been observed.

The zones in which basic plagioclase and augite are the main constituents show a varying grain size. For the greater part the plagioclase occurs in minute crystals of which the size is about 0.01—0.03 mm. Polysynthetic twinning is often observed. Plagioclase-rich and augite-rich parts often alternate in more or less parallel narrow bands and the longer axes of the augite crystals show a tendency to be arranged parallel to these bands. The augite crystals range up in size from 0.005 mm in the smallest grains to 1.2 mm in the largest observed skeleton. The large crystals sometimes consist of separate parts with simultaneous extinction. Their colour is brownish to greenish grey, purplish grey tints are more particularly found in the right part of the figure between the spots which are rich in leucite. Especially in this part a residual cement, consisting of leucite, is clearly developed between the plagioclase grains. Many, mostly irregular, crystals of titanite occur in the assemblage; other constituents are calcite and some grains of iron ore. Flakes of brown biotite were observed locally. A larger size of the plagioclase (up to 0.5 mm) is found at some places near the border of the fragments of wollastonite-rock and the colour of some of the augites is a little darker there. The largest size of the plagioclase crystals (up to 1 mm) was observed in the upper left part of the figure where the characteristics of the assemblage are similar to those in figures 1 and 2. In irregular spots in wollastonite, which are shown in the right middle part of the figure, the main constituent is greenish to brownish grey augite of varying size. Larger skeletons reach up to 1 mm in diameter. Plagioclase, calcite and iron ore are found in subordinate amount; the size of the plagioclase crystals does not exceed 0.1 mm.

In the leucite-rich assemblages leucite and augite, whether or not with plagioclase, are the main constituents. They mostly form spots in the plagioclase-augite mixture in the right part of the figure. These spots, which are roughly shown in the figure, range down to a very small size and pass into the leucite cement between the grains of the adjacent plagioclase-augite mixture, which is also found enclosed in the spots. The spots contain minute grains and larger prismatic and irregular crsytals of greenish grey and purplish grey augite, which reach up to 0.75 mm in size. The leucite forms a base in which the other minerals are embedded and the boundaries between the individual crystals are not distinct. Besides the leucite-rich assemblages, in which plagioclase grains similar to those of the adjacent mixture are enclosed, there are also assemblages in which the plagioclase is partly of larger size. These parts are shown with a different signature in the upper part of the figure. The plagioclase is up to 0.2 mm in diameter, it is of very basic composition and sometimes shows a zonal structure with a more acid rim. Good crystal boundaries are often found. The grey to greenish grey augite reaches up to 0.5 mm in size, it often shows good crystal boundaries but it also forms skeletons of which isolated parts extinguish simultaneously. Other constituents are calcite, titanite, some minute crystals of iron ore and an interstitional glass-bearing substance similar to that of the leucitephonolite, which will be described below.

In the bifurcating zones or veins of leucitephonolitic composition the leucite crystals are mainly arranged along the border, which may for some distance consist of a continuous band of leucite; these bands are not shown in the figure by a different signature. Some crystals are found as small phenocrysts, which are entirely surrounded by the glass-bearing groundmass of the inner part of the zones. Leucite is lacking in the narrower, trachytic, parts of the glass-bearing zones in the right upper part of the figure. The leucite crystals are from 0.2 to 0.75 mm in diameter. They show optical anomalies, they partly contain narrow veins of calcite and they may enclose small plagioclase grains and augite crystals of different size. The greenish grey augite is also found in separate crystals of phenocrystic size. The groundmass contains potash-rich felspar, brownish amphibole, light greenish to nearly colourless augite and glass. Basic plagioclase, titanite and iron ore are present in small amount. Some leucite crystals have about the same size as the largest constituents of the groundmass, which is strongly vesicular;the vesicles are partly filled with calcite. The lath-shaped crystals of potash-rich felspar show parallel or nearly parallel extinction; they are up to 0.2 mm in length. Small microlites with a length of about 0.01—0.03 mm are numerous. The larger crystals may surround a small core of basic plagioclase, which reaches up to about 0.03 mm in diameter. Small plagioclase grains without a rim of potash-rich felspar are also found. The amphibole crystals have an irregular or more or less prismatic shape and reach up to 0.1 mm in length. Their colour is mostly brown but various shades of brown, bluish purple and green tints are sometimes found in the same crystal. The low double refraction, the negative elongation and the large extinction angles (up to 35°) point to an alkali-amphibole with affinities to katophorite. The interstitional glass shows slight devitrifcation.

The continuous bands of leucite crystals along parts of the border of the glass-bearing zones may resemble the holocrystalline leucite-rich assemblages outside these zones, which are shown by a different signature in the figure. The glass-bearing zones contain potash-rich felspar and amphibole. Potash-rich felspar is found in holocrystalline assemblages in other parts of the rock (comp. figs. 3 and 13) but amphibole appears in the glass-bearing parts only. This indicates that the stability field of amphibole was reached shortly before the final consolidation of the last residual liquid.

Fig. 6.

Limestone is absent in this figure. Large parts of the wollastonite-rock contain numerous crystals of greenish grey augite, which are often accompanied by calcite and small amounts of plagioclase or potash-rich

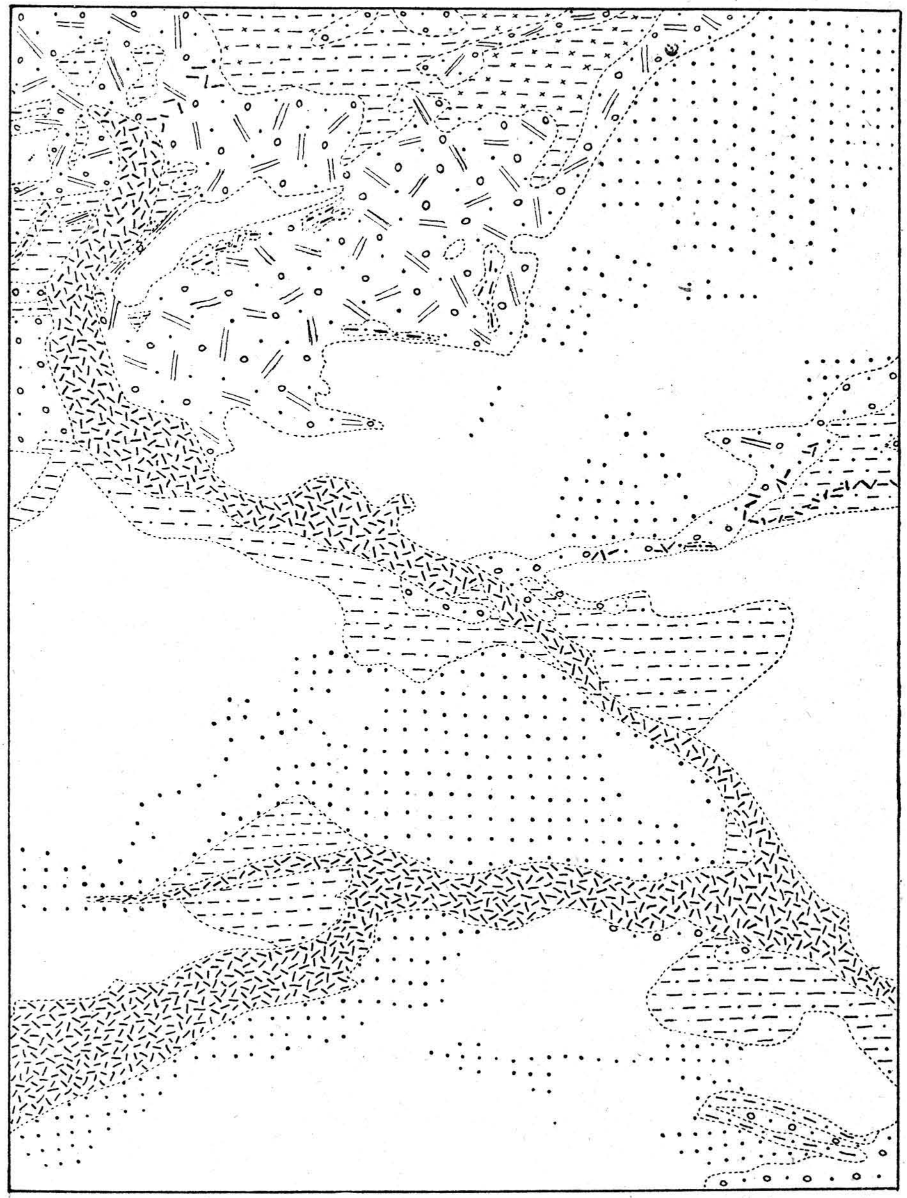

Fig. 6. Enl. × 6.

felspar. These parts are roughly shown in the figure. The larger crystals of augite are skeletons, which reach up to 0.6 mm in size. Pyrrhotite is a rare constituent of the wollastonite-rock and gehlenite seems to be absent.

The assemblages in which plagioclase and augite or plagioclase and biotite are the main constituents resemble those in fig. 3. Locally augite and biotite are found together but mostly they are separated in space. The average size of the plagioclase and biotite crystals is about 0.01 mm, the largest crystals are up to 0.05 mm in diameter. Skeletons of augite may reach up to 0.7 mm and irregular crystals of titanite may reach up to 0.1 mm in size. Small crystals of magnetite and pyrrhotite occur in small amount. Leucite and potash-rich felspar are found as an interstitional cement in these assemblages.

The two last-mentioned minerals are found in crystals of larger size in the assemblages in which leucite and augite or leucite, potash-rich felspar and augite are the main constituents. The average grain size varies from about 0.06 to 0.4 mm but locally the crystals of potash-rich felspar reach up to 1.5 mm in length and the same size is reached by some larger skeletons of augite. Smaller crystals of augite often show good crystal boundaries, their colour mostly varies from greenish to purplish grey. Some crystals are almost colourless. A greenish rim surrounding a colourless core with smaller extinction angle is sometimes observed. Calcite, titanite and iron ore are constituents of minor importance while wollastonite is found locally, especially near the boundary of the wollastonite-rock.

The leucitephonolite and trachyte are strongly vesicular and resemble those in fig. 5. The leucite crystals are up to 0.9 mm in diameter, are mainly found along the border of the zones or veins (fig. 14) and are lacking in parts of them; these parts have a trachytic composition. Small phenocrysts of potash-rich felspar, which reach up to 0.25 mm in length are observed locally. The lath-shaped crystals of potash-rich felspar in the groundmass sometimes have minute cores of basic plagioclase. The amphibole with affinities to kataphorite shows different colours, often with the lightest colour in the marginal part. The numerous vesicles are partly empty and partly contain calcite.

Fig. 7.

The fragments of wollastonite-rock show similar characteristics as those in fig. 6. In the left lower part of the figure the limestone is not yet altered entirely into wollastonite (with some gehlenite and pyrrhotite). Larger crystals of wollastonite and gehlenite reach up to 0.8 mm in size but the grain size is mostly much smaller (about 0.1 mm). A fine grained gehlenite-rich zone with an average grain size of about 0.1 mm is found between the partly altered limestone and the surrounding plagioclase-augite zone. This gehlenite-rich zone is absent where the limestone is entirely altered. The gehlenite-rich zone also contains wollastonite, garnet, augite and calcite; its mineralogical composition resembles that in the left lower part of fig. 3 where its presence is also connected with a core of limestone in the lime silicate assemblage.

The assemblages in which plagioclase and augite or plagioclase and biotite are the main constituents resemble those of fig. 3. They contain numerous leucite-bearing spots (fig. 12), which are roughly shown in the sketch.

Assemblages in which leucite and augite, potash-rich felspar and augite,

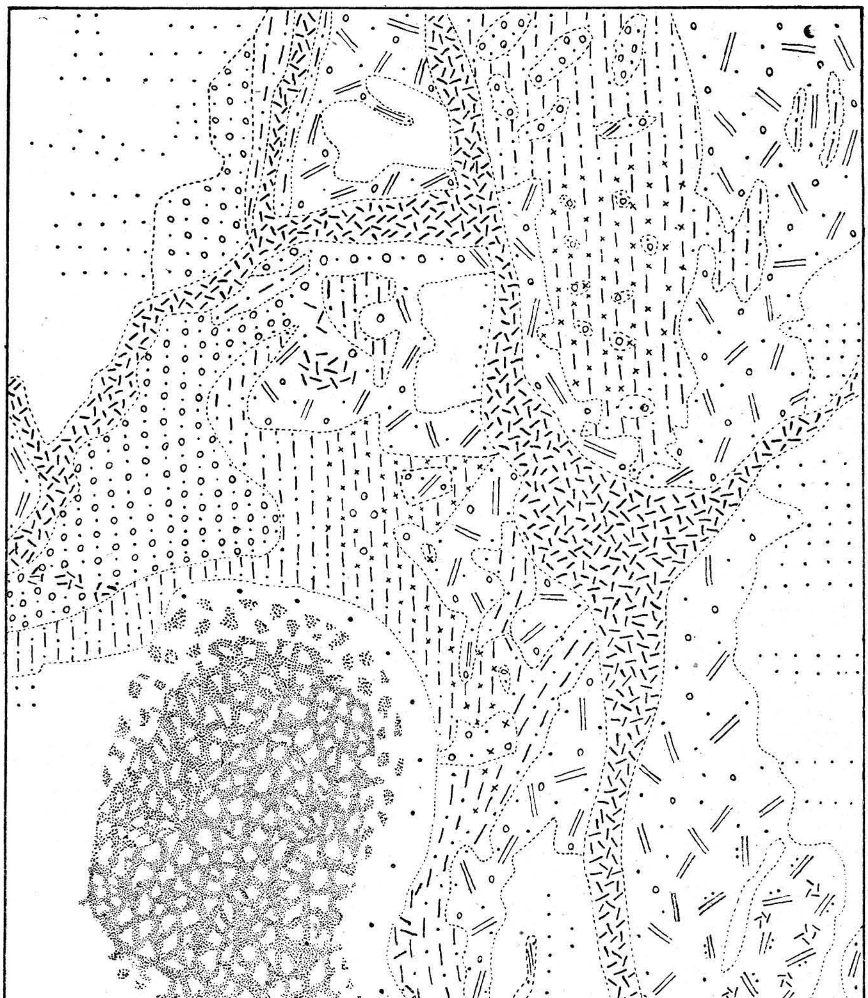

Fig. 7. Enl. × 6.

or leucite, potash-rich felspar and augite are the main constituents cover a large part of the figure. The grain size is varying; the crystals of potash-rich felspar vary from 0.06 mm to 1 mm in size, some crystals of leucite reach a diameter of more than 1 mm and the size of the augite crystals ranges up from less than 0.02 mm in the small grains to 1.5 mm in the

Fig. 8.

Beginning alteration of limestone into wollastonite and gehlenite as shown in the upper part of fig. 2. Slightly recrystallized limestone in the central part of the figure. Dark spots and zones with small crystals of wollastonite and gehlenite show the first stage of alteration. More crystals of wollastonite and gehlenite in the upper and lower parts of the figure. Ordinary light. × 50.

Fig. 9.

Protruding sector of the outer zone around a limestone lenticle. The main constituents of the core in the left lower part of the figure are gehlenite, wollastonite, augite and iron ore. The augite content increases towards the margin, the outer rim consists of augite and calcite. Augite crystals of the plagioclase-augite mixture (comp. fig. 3) in the upper and right part of the figure partly lie inside the outer rim. Ordinary light. × 24.

Fig. 10.

Strongly vesicular, pyroxene-rich section in the right upper part of fig. 3 with small crystals and larger skeletons of pyroxene in a slightly devitrified glass. The vesicles are irregular in shape and mostly empty. Ordinary light. × 46.

Fig. 11.

Zonal arrangement of different mineral assemblages in the right upper part of fig. 1. Wollastonite in the left part of the figure, farther to the right plagioclase and augite (two white plagioclase crystals are clearly visible). In the right half of the figure: leucite, augite and wollastonite with some calcite. Nicols crossed. × 18.

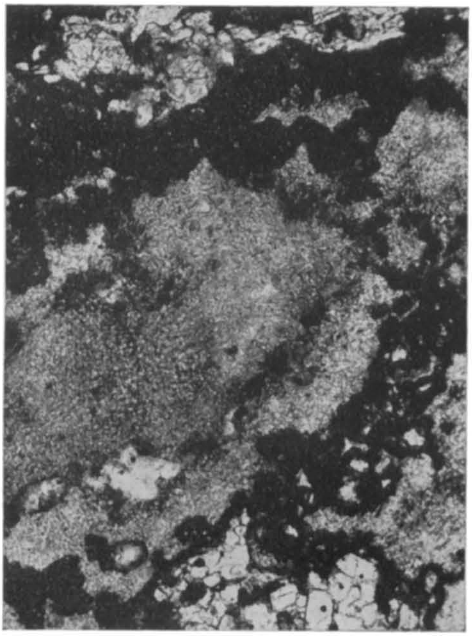

Fig. 8.

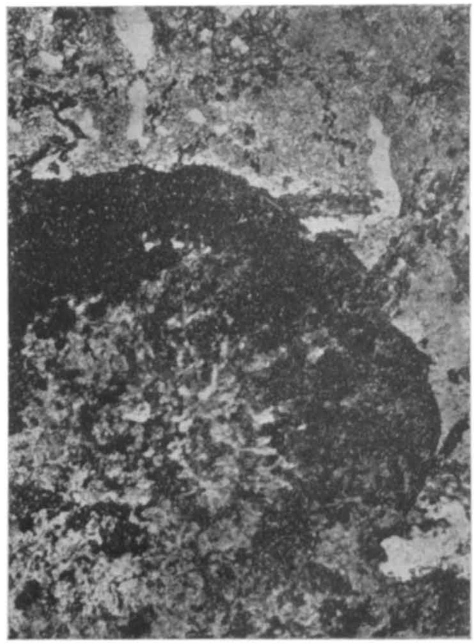

Fig. 9.

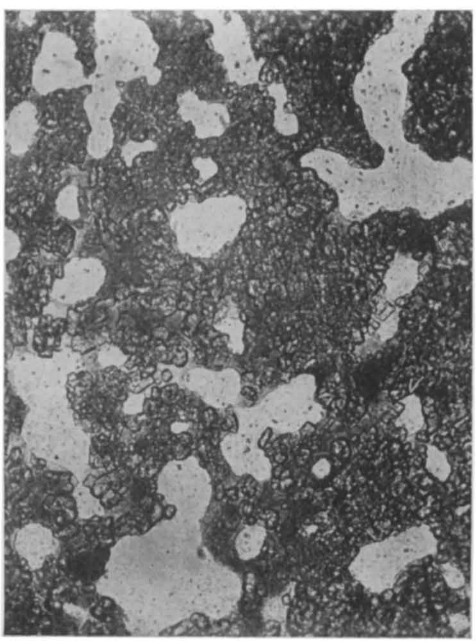

Fig. 10.

Fig. 11.

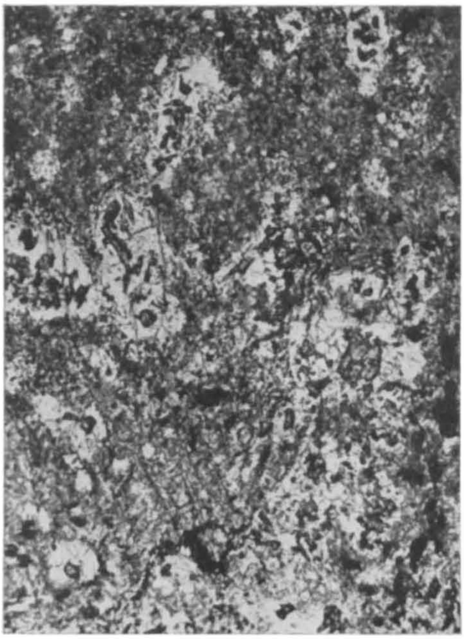

Fig. 12.

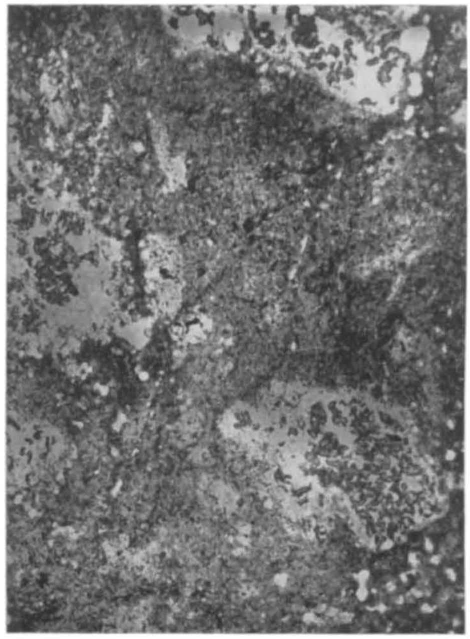

Fig. 13.

Fig. 14.

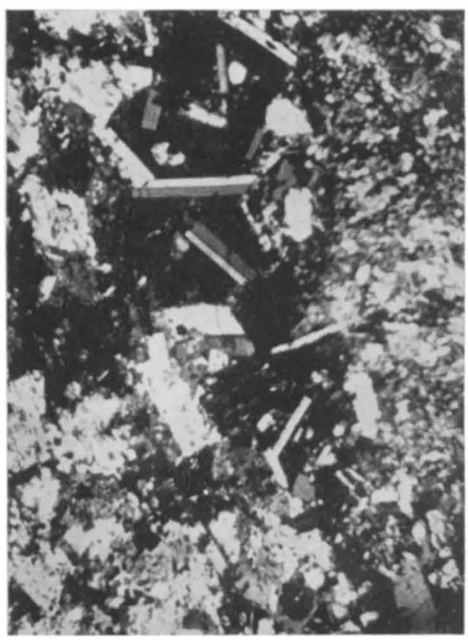

Fig. 15.

Fig. 12.
Leucite-rich spots in a fine-grained mixture of plagioclase and augite or plagioclase and biotite, as shown in the upper part of fig. 7. The spots contain leucite, augite and sometimes biotite. Ordinary light. × 29.

Fig. 13.
Spots containing potash-rich felspar, augite and sometimes biotite in a fine-grained mixture of plagioclase and biotite, as shown in the left part of fig. 3. Ordinary light. × 18.

Fig. 14.
Vesicular leucitephonolite in the lower half of fig. 6. The leucitephonolite is seen from the left lower to the right upper part of the figure. The vesicles are irregular in shape and mostly empty. The leucite crystals are found in the marginal parts of the vein; near the left border they are especially numerous while near the right border they are only found in the upper and lower parts of the figure. The crystals have euhedral and rounded forms and often carry more or less concentric inclusions. The leucitephonolite is bounded on both sides by wollastonite-rock, which is poor in augite in the right part and rich in augite in the left part of the figure. Ordinary light. × 16.

Fig. 15.
Trachytic zone with phenocrysts of potash-rich felspar in a glass-rich vesicular base. The zone pinches out near the right lower corner of the figure. To the right of the trachyte is a zone consisting of gehlenite and wollastonite, which, outside the figure, borders upon a limestone lenticle. To the left of the trachyte is a zone consisting of plagioclase and augite with interstitional glass-rich spots containing microlites of potash-rich felspar. Farther to the left, outside the figure, the main constituents of the alternating zones are wollastonite and augite or plagioclase and augite. Nicols crossed. × 14.

largest observed skeleton. The colour is somewhat varying from greenish grey to nearly colourless, while a greyish to brownish green colour seems to prevail in the leucite-rich assemblages. Titanite and iron ore are minor constituents; with numerous small crystals of augite they are enclosed in potash-rich felspar and in leucite. Calcite and wollastonite occur locally. Glass-bearing spots with microlites of potash-rich felspar are exceptionally found. In the right lower part of the figure brown glass and calcite are found in a mixture of augite, wollastonite and potash-rich felspar. Most of the glass is found in the bifurcating zones of leucitephonolitic and trachytic composition, which are similar to those of figures 5 and 6.

Replacement of the limestone and production ol alkali rocks.

The figures and petrographic descriptions in the foregoing pages show that the limestone has for the greater part been converted into silicates. The lenticles and strings, which have not been converted, consist of a rather pure calcium carbonate. This indicates that permeation of the limestone by magmatic solutions was the principal cause of the metamorphic changes. It seems that fissuring has facilitated the permeation to a certain degree and a more forcible injection process may also have contributed to the invasion of magmatic substances.

A succession of crystallization of the different minerals can be noted but their periods of formation overlap. Later minerals may replace the earlier ones. It is often clear, that the succession of the principal constituents began by wollastonite and gehlenite, that augite and plagioclase are later and that potash-rich felspar and leucite are still later. There is a tendency for the potash-rich felspar to occur as mantles about plagioclase as is the case in alkali rocks from some Javanese and other volcanoes [1]. Gehlenite, wollastonite and augite may have continued to develop until a late stage of the metamorphic process, especially where they are found around a core of limestone (figures 3, 7, 9).

The mineralogical composition of the metamorphic rock shows that many substances — chiefly silica, alumina and alkalies — have been introduced into the limestone. Carrying away of calcium oxide and liberation of carbon dioxide could compensate this addition of substances. Evidence of inoculation of the surrounding magma by introduction of calcium oxide may be found in the more or less rounded glass-rich and strongly vesicular sections in the upper part of fig. 3, which occur at the surface of the limestone block and which are very rich in crystals of light-coloured pyroxene. These crystals lie in a slightly devitrified brownish to colourless glass (fig. 10). Liberated carbon dioxide could assist in decreasing the

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[1]) J. P. IDDINGS and E. W. MORLEY. Contribution to the petrography of Java and Celebes. Journ. of Geol., 23, 1915, p. 231—245. N. L. BOWEN. The evolution of the igneous rocks, 1928, p. 229 and 250.

viscosity and may explain the abnormal development of vesicles and the growth of comparatively large pyroxene skeletons (fig. 10).

Evidence of a special phase of crystallization differentiation may be found in the spots which contain potash-rich felspar or (and) leucite (figs. 3, 7, 12 and 13). There is a sharp break in composition and grain size between the spots and the surrounding mineral assemblage which is rich in basic plagioclase. Volatile constituents, which carried the alkalies with them may have concentrated in the spots where they decreased the viscosity of the residual liquid. The abundance of volatile constituents is particularly well illustrated by the strongly vesicular character of the phonolite, trachyte and trachyandesite. Limited differentiation may also have influenced the zonal arrangement of. different mineral assemblages.

The connection between the undersaturated rocks and the typical Merapi lava has not been observed as this lava was not found adherent to the metamorphic limestone. It is, however, clear that in a volcano, which erupts pyroxeneandesites, a great variety of alkali rocks has been produced on a small scale in association with limestone. This production was limited in space and time and it raises the question whether a large scale production of alkali rocks by reaction of igneous magma with limestone, under more favourable conditions, was realized in extinct volcanoes near the north coast of the eastern part of Java where the volcanic rocks are largely alkali-rich [1]).

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[1]) H. A. BROUWER. loc. cit.