CONTRIBUTIONS TO THE GEOLOGY OF THE EAST INDIES FROM THE SNELLIUS EXPEDITION

Part I Volcanoes

BY

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(Rock analyses by CATHARINA KOOMANS)

CONTENTS:

1. GENERAL INTRODUCTION TO THIS SERIES.

The oceanographical expedition on board Hr. Ms. Willebrord Snellius spent 15 months in investigating the eastern part of the Netherlands East Indies from 1929 to 1930. The present author accompanied the expedition as geologist.

The geological results of the expedition may be devided into two parts. The first comprises those subjects that stand in direct relationship to the oceanographical work of the expedition, viz: the geological interpretation of the bathymetrical data obtained, the geology of coral reefs and the bottomsamples. These subjects are to be dealt with in the reports of the expedition. Two volumes have already appeared:

The Snellius-Expedition, Volume V: Geological Results, Part 2: Geology of Coral Reefs, by PH. H. KUENEN, Kemink en Zoon, Utrecht (Holland), 1933.

Part 1: Geological interpretation of the bathymetrical results, by PH. H. KUENEN, 1935.

The second part of the results of the expedition appertains to the regional geology of the East Indies, and is to be published separately as: Contributions to the geology of the East Indies from the Snellius Expedition. This paper forms the first part of the series.

The specimens, slides, etc. are deposited in the Rijksmuseum van Geologie, Leiden, Holland, while a duplicate collection is to be sent to the museum of the Dienst van den Mijnbouw in the Netherlands East Indies, at Bandoeng, Java.

In the Snellius-Expedition, Vol. V, Part 1, a discussion will be found of the submarine slopes of the East Indian volcanoes and in bibl. 21 an experimental investigation of the slopes of volcanoes in general.

2. THE PENANGGOENGAN (fig. 1—8)

A. Morphology.

The Penanggoengan is a comparatively small volcano, 1653 m high, situated 50 km south of Soerabaja in eastern Java. It can be looked upon as the northern outpost of the group Ardjoeno-Welirang.

VERBEEK in his description of Java (bibl. 30, dl. I, p. 140, 200—201; dl. II, 949, 956) mentions the Penanggoengan as a regular cone, with a small crater at the summit, the shape of which is complicated by a number of mounds on the slopes. He is in doubt whether to ascribe these to lateral eruptions or to an older crater rim. He believes that the steep cliffs on the low hills G. Sari and G. Prahoe were formed by abrasion during a higher stand of sea level. He also mentions the occurrence of various andesite lava's and tuffs.

The writer was able to spend ten days on the investigation of this volcano, the excellent topographical map forming a welcome basis for

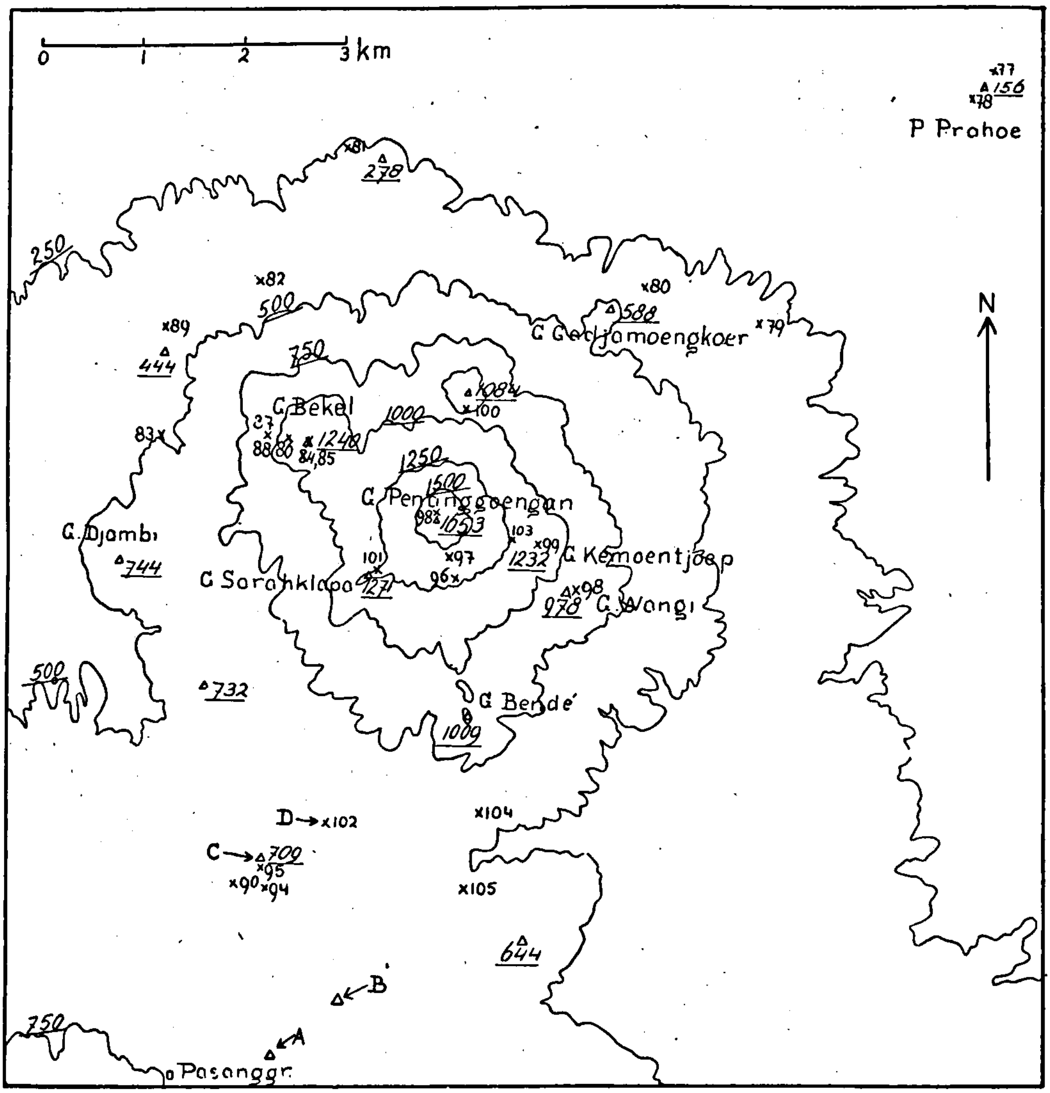

Fig. 1.

Map of the Penanggoengan, scale 1 : 75.000.

the geological observations. It was found that the more striking irregularities of the cone are all due to lateral eruptions and that, although the precise nature of some of the lower ones remains somewhat doubtful, there is certainly no part of an old *craterrim* exposed.

The G. Sari (now G. Bang on the topographical map) is situated at a greater distance and was not visited by me. The G. Prahoe (150 m) lies at the foot of the slope and formerly possessed a low domed shape, of which the western half is now missing.

As only one side has been attacked, this can hardly be attributed, as VERBEEK did, to abrasion that would have encroached on all sides or on the north-east more in particular. It appears almost certain that a former loop of the river Kali Porong meandered up against the G. Prahoe. It was only prevented from eroding away the entire mound by the gradual approach of the growing slopes of the Penanggoengan

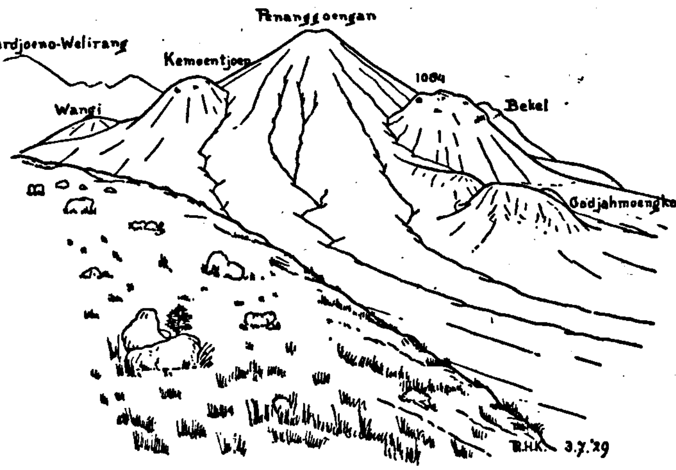

Fig. 2.

The Penanggoengan seen from the P. Prahoe in the northeast.

that forced it away to the north. This process is also indicated by the manner in which the lower reaches of the Penanggoengan-slopes are carefully lapped around the adjoining end of the G. Prahoe.

It is true that this explanation cannot hold for the G. Sari as well, as it lies far away from the river. If the contours of the map are correct, however, the steep cliff could neither have been formed by abrasion in its protected position.

The general shape of the G. Prahoe might suggest that it is a shield volcano. If this surmise were correct the large blocks scattered over the surface (see fig. 2) were probably formed out of irregularities by weathering. VERBEEK, however, mentions conglomerate tuffs, so that the G. Prahoe is more probably a parasitic cone without a crater.

On the southwest side a number of small eruption points are situated between the Penanggoengan and the Welirang, to both of which volcanoes they could be attributed. They rise only a few dozens of meters above the surroundings. Two are young conelets with lateraly opened craters (C and D on map, fig. 1). A third, somewhat larger hill (B), probably also has an opened crater, but dense growth prevents a clear view of the situation. A fourth small cone (A) has no visible crater.

High upon the main cone four large bulges jut out from the regular conical form of the volcano.

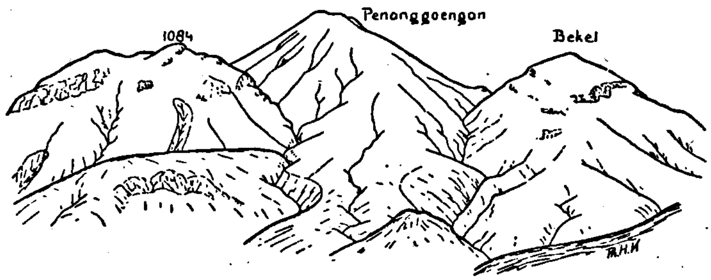

Fig. 3.

The Penanggoengan seen from the north, close to point 278.

From all sides they may be seen from a great distance and they lend a peculiar aspect to the profile of the mountain. They are the G. Wangi (978 m), the G. Kemoentjoep (1232 m), an unnamed hill of 1084 m and the G. Bekel (1240 m). Closer investigation shows them to be typically developed lava plugs (tholoïden) [1]) formed by very

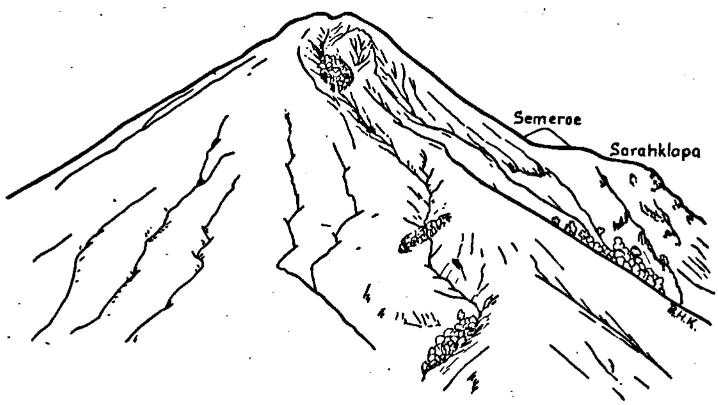

Fig. 4.

Summit of the Penanggoengan seen from the G. Bekel.

viscous lava that oozed out of lateral openings on the main cone. The molten rock was so viscous that it only sagged down the steep slopes

[1]) Some authors use the term „dome''. In order to avoid possible confusion it must be pointed out that here we do not mean necks.

of the volcano for a short distance. Subsequent crumbling of the rock covered up the base of the plugs in steep screes, from which it follows, that the original incline of the tholoïden slopes was greater than that of screes of rough blocks.

The nature of these curious mounds may be deduced from the absence of a crater, the knobbly but rounded summit (see fig. 2, 7) and the absence of lava flows. As the backward working erosion in the screes has hardly or not yet reached the protruding masses of hard rock at the summit, the latter must be primary and cannot be attributed to lava flows that have been laid bare by denudation.

Lower down on the slopes of the Penanggoengan there occur four curious hills, for which it is more difficult to find a satisfactory explanation. On the north side lies the G. Gadjamoengkoer (588 m); on the east side the G. Djambi (744 m); south of the latter a nameless hill (732 m); finally to the south the G. Bendé (1009 m). They differ from the former group not only by their position towards the foot of the volcano, but also by their more complicated shape, the more or less horizontal edge connecting them with the main cone and the dense growth indicating further advanced weathering of the rock.

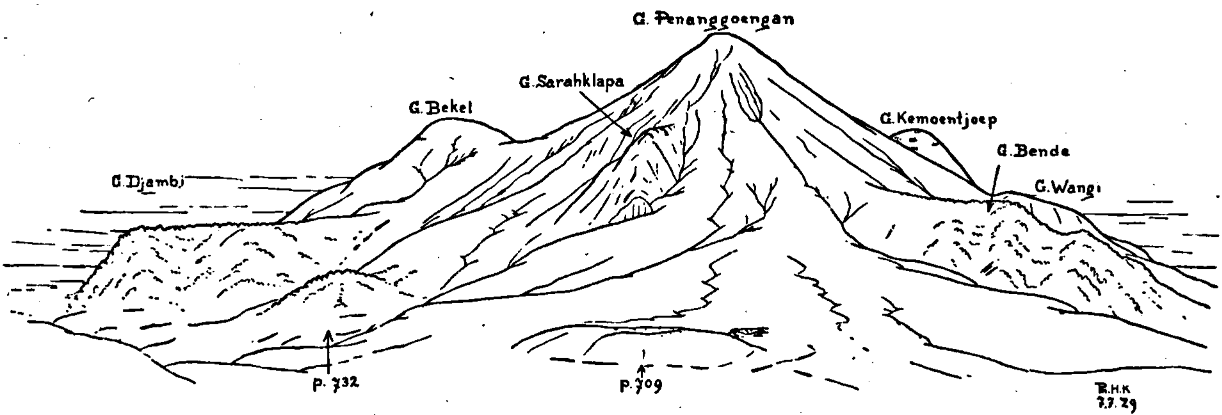

Fig. 5.

The Penanggoengan seen from the pasanggrahan in the south.

The latter property indicates greater age, especially as they appear to be formed of massive lava. The same conclusion is to be obtained from the manner in which the G. Gadjahmoengkoer has shielded off the products of the main cone; visible especially on the eastern side. The simplest explanation would be that these hills are the remains of a much eroded volcanic ruin, the centre of which has subsequently been buried below the younger Penanggoengan.

There are, however, some objections to this hypothesis. In the first place the horizontal ridge of the G. Djambi and the G. Bendé (see fig. 5) can hardly be claimed as a normal erosion form. In the second place the same two hills show little influence on the construction of the central mountain, from which it would follow that they must be comparatively recent formations. The last point and the question of the composition either of massive lava or of tuffs and flows calls for detailed investigation and would justify a renewed examination in the field. Finally the G. Sarahklapa, that has not yet been mentioned, forms a kind of link between these hills and the normal plugs.

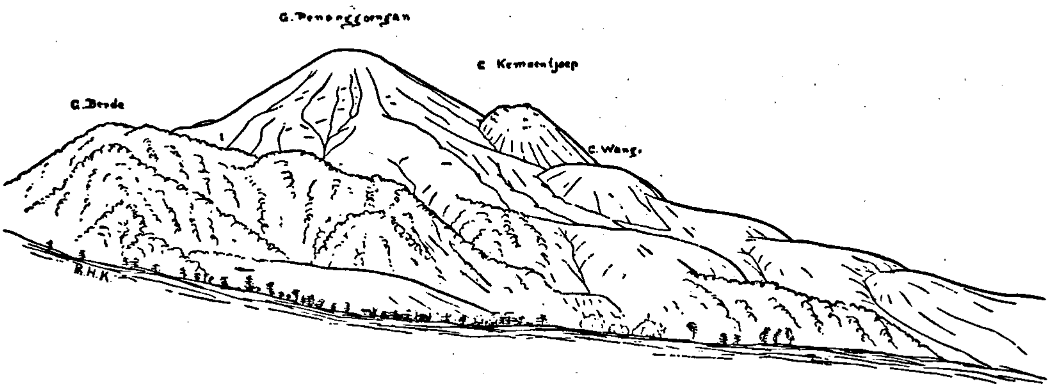

Fig. 6.

The Penanggoengan seen from the southeast.

The G. Sarahklapa, namely, is situated high up on the Penanggoengan (1271 m) and is of simple form. On the other hand it is covered with trees and is connected with the main cone by its horizontal, ridge-shaped summit.

Fig. 7.

The lava plug (tholoïde) of point 1084 seen from the summit of the Penanggoengan.

On account of these objections to the explanation first given, I proposed in my preliminary report (bibl. 20) that the lower protrusions might have been formed as plugs above radial fissures, possibly with

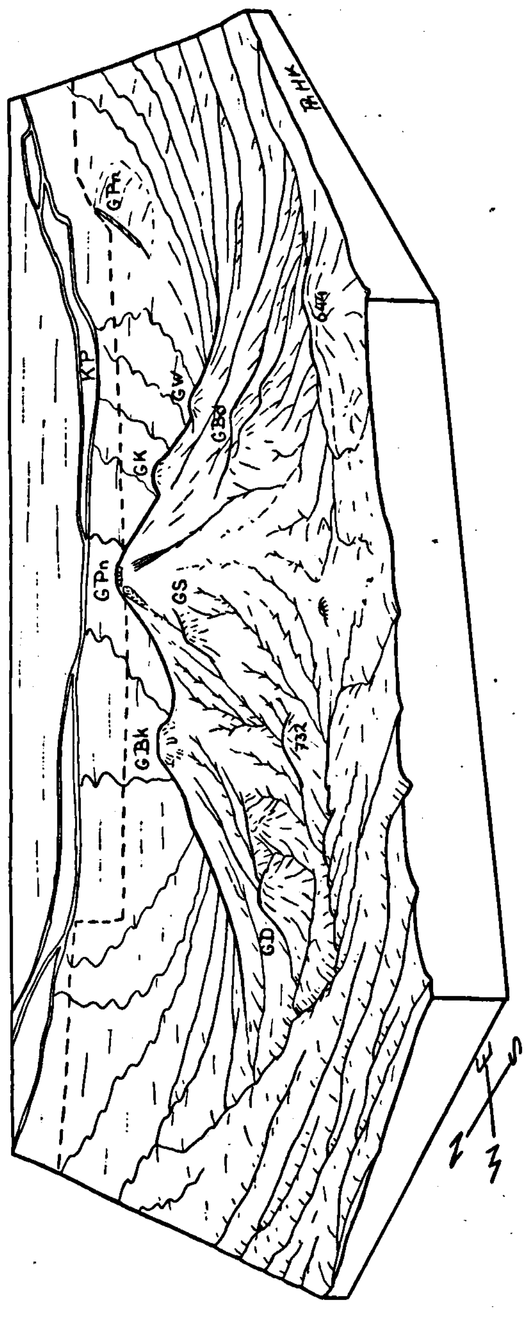

Fig. 8.

Blockdiagram of the Penanggoengan seen from the southwest.
GD = G. Djambi; GBk = G. Bekel; GS = G. Sarahklapa;
GPn = G. Penanggoengan; GK = G. Kemoentjoep; GBd = G. Bende;
GW = G. Wangi; KP = Kali Porong; GPr = P. Prahoe.

lateral outporings from their own flanks. As I am not aware, however, of this process ever having been observed on active volcanoes I now incline to the other view that they are the remains of an older, almost buried structure. It is to be hoped that future investigation will bring a satisfactory solution of this problem.

The main cone of the Penanggoengan is of remarkably regular shape. Only on the western side has erosion had any appreciable influence on the general form (fig. 4). For the greater part the surface is covered with thin lava flows, but tuffs of various degrees of coarseness are by no means absent, especially on the lower slopes.

At the summit a small, well preserved crater of 100 × 150 m and 20 m deep is found. It is divided more or less in two separate parts.

According to v. HINLOOPEN LABBERTON (bibl. 17, p. 137) the volcano has been extinct at least 1000 years. The last eruption may have occurred about the year 200.

B. Petrography.

Twenty six rocks were examined under the microscope and Miss KOOMANS made three chemical analyses.

Both in the hand specimen and microscopically there is a considerable variation in the rocks of the Penanggoengan, both basalts and andesites being represented.

Three types of rock can be distinguished according to the composition of the plagioclase with corresponding, but less marked, typical association with dark constituents.

1. *True basalts.* (78, 79, 81, 84, 86, 87, 94, 95, 96 (Analysis), 101, 102, 103, 105). Dark grey or brown, generally porous rocks. The plagioclase phenocrysts contain 80—95 % An in the large core, (18 determinations Universal Stage), ranging down to about 60 % in the narrow outer border (8 determinations U. St.), the smaller- and groundmass crystals contain from 60 to 70 % An (3 determinations U. St.). As dark phenocrysts we always find a pale green, slightly pleochroïc augite (often with zoning, dispersion of the bissectrix and hourglass structure); olivine is generally present (79, 81, 84, 95, 96, 101, 102, 103, 105). Hypersthene was only found in 78. Decomposed hornblende in small amount occurred in a few slides (78, 81, 84, 94, 95); well preserved reddish brown hornblende in larger amounts is typical of the Bekel rocks (86, 87). All contain magnetite. The groundmass contains the same minerals as the phenocrysts and some glass.

2. *Acid basalts.* (77, 83, 89, 90 (Analysis), 97, 104). Light to dark grey, mostly compact rocks. The plagioclase phenocrysts contain 60—75 % An in the core (9 determinations U. St.), ranging down to about 50 % in the border (4 determinations U. St.). The larger groundmass crystals contain about 60 % (1 determination U. St.). One specimen (90) contained a few larger crystals the core of which contained about 90 % An. All except one (104) contain augite as phenocryst, but this rock contains a small amount of hypersthene in the groundmass. The latter mineral is found as phenocryst in two (77, 89). Olivine occurs

as phenocryst in 77 and in the groundmass of 97. Decomposed hornblende is a rare phenocryst in all, but is of more importance in 104. All contain magnetite.

3. *Andesites.* (92, 98, 99 (Analysis), 100). Light grey to yellow, porous spickled rocks. The plagioclase phenocrysts contain 40—50 % An, in 98 about 60 % An (5 determinations U. St.). They all contain a reddish brown, strongly pleochroïc hornblende in elongated, idiomorphic crystals in considerable amounts. Augite is found in all except 92, hypersthene in one (99). Olivine occurred in one slide (92) but was evidently an accidental inclusion. All contain magnetite. The groundmass shows a considerable amount of glass with crystallites and the same minerals as the phenocrysts.

The chemical differences between these types, especially between the two latter, is much smaller than would be expected from the mode, (see below under petrology). Evidently the variations in the physical conditions played a greater part in producing the types, than did the composition of the magma. This surmise is born out by the fact that in a number of the rocks the hornblende became unstable in the later periods of development and was reduced to a mixture of plagioclase, pyroxene and ore.

In all three types we frequently encounter small inclusions of the dark constituents with plagioclase. This indicates that in all probability all these minerals contributed to the differentiation.

Concerning the connections between the petrography and the morphological forms a few rules can be formulated.

a. The andesites are restricted to the lava plugs (Gn. Boetak, Gn. Wangi, Gn. Kemoentjoep, p. 1084).

b. All the plugs are characterised by the occurrence of hornblende as normal and predominating dark phenocryst (those mentioned under *a*, and the Gn. Bekel) while outside these, hornblende is always rare and moreover greatly decomposed. Handspecimen 104 is rich in hornblende, but it was taken at the foot of the Gn. Bendé, one of the doubtfull plug masses. Only the Gn. Sarahklapa appears to lack hornblende, but this lava plug (?) is of slightly different shape to the others.

Mention must also be made of three exceptional handspecimens:

Nr. 80 is an inclusion in tuff belonging to the true basalts (plagioclase about 85 % An, with rims of about 55 % (2 determinations U. St.), but containing, strongly pleochroïc hornblende (olivegreen-yellow, c/b 15°), and intersticial glass with bubbels.

Nr. 88 was also an inclusion judging by the holocrystalline, granitic structure. The zonal plagioclase contains 80—85 % An (one determination U. St.), while augite and brown hornblende are also present as phenocrysts.

Nr. 82 is a curious metamorphosed rock, containing pyrites and with epidote in the centre of the plagioclase. It contains phenocrysts of plagioclase, biotite, and greenish hornblende.

Miss KOOMANS analysed three rocks with the following results:

	96	90	99		96	90	99
SiO_2	52.43	56.52	56.78	si	138	169	175
TiO_2	0.70	0.49	0.58	al	28	31.5	31
P_2O_5	0.25	0.22	0.20	fm	38	32.5	34
Al_2O_3	18.05	17.87	17.47	c	24.5	21	19
F_2O_3	5.32	3.69	3.27	alk	9.5	15	16
FeO	3.63	1.91	1.44	ti	1.4	1.1	1.7
MnO	0.16	0.17	0.13	p	0.32	0.36	0.37
MgO	4.91	4.18	4.79	h	13.7	26.1	36.6
CaO	8.68	6.61	5.66	k	0.30	0.29	0.28
Na_2O	2.62	3.72	3.85	mg	0.51	0.58	0.65
K_2O	1.67	2.25	2.29	c/fm	0.64	0.66	0.55
$+H_2O$	0.95	1.90	2.30	qz	0	+ 9	+ 11
$-H_2O$	0.61	0.71	1.27				
	99.98	100.24	100.03				

The analyses show, that the true basalt no. 96 has a normal intermediate composition. Al_2O_3 is comparatively high. The acid basalt no. 90 is also normal in chemical composition. The andesite no. 99 has the composition of an acid basalt or an intermediate andesite with comparatively low content of iron.

The acid basalt and andesite belong to NIGGLI's normal dioritic magma; the true basalt to the gabbro dioritic magma. The following micrometric analyses were made:

	nr. 96	nr. 90	nr. 99
plagioclase	37 %	26 %	21 %
augite	7 %	3.5 %	5 %
hornblende	—	1.0 %	3 %
magnetite	1 %	3.5 %	2 %
olivine	5 %	—	—
glass	50 %	66 %	66 %
vesicules	—	—	3 %

3. THE TENGGER CALDERA (fig. 9—11).

It is not my intention to enter into the problem of caldera formation in general or of the Tengger in particular, but a visit to this famous volcanic centre enabled me to make an observation that is of some importance in connection with the doubtless complicated history of the caldera.

The caldera consists of three distinct parts, the great southwestern basin, the smaller northeastern basin, the valley of Sapikerep that forms the outlet of the latter. The former two are divided by a curious straight dam, the Tjemoro Lawang.

VERBEEK and FENNEMA (bibl. 30), who investigated the Tengger, came to the conclusion that at one time in the history of the group there existed a double volcano and that two large caldera's were formed side by side and that the valley of Sapikerep was broken out by a lava flow from the northeastern crater. Afterwards lava rose in the southwestern caldera, flowed over into the other and thence down the valley of Sapikerep. Finally the lava sea sank back slightly in the first caldera, forming the substratum of the sandsea and the later small eruption points.

ESCHER, on account of the absence of a dejection cone at the end of the valley of Sapikerep, ascribed this feature to gradual erosion by streams (bibl. 13). Although he postulates a different manner of formation for the caldera's, he follows VERBEEK and FENNEMA in the main lines of their theory. According to ESCHER the eruption cores out a cylinder that is widened out to a caldera by the crumbling down of the sides of the cylinder until a funnel-shape is produced.

AKKERSDIJK, following ESCHER's plea for field observations on this interesting problem, spent some time on field work that led him to important alterations of the above history (bibl. 1, 2). There was only one main cone, with minor parasitic cones. First a caldera was formed in the northeast with a tongue-shaped extension, the valley of Sapikerep. The latter is therefore looked upon as the result of subsidence. The presence of hanging valleys along this great breach of Sapikerep lends support to this view. The shape of the caldera was further complicated by irregular crumblings that carried away the gaps now existing between jutting spurs on the inner slopes of the cauldron. Later eruptions filled up the caldera and the products overflowed into the valley of Sapikerep, thus producing the gradual slope from the Tjemoro Lawang right down into this valley.

In a later stage the southwestern caldera was formed also by subsidence. The straight course of the Tjemoro Lawang can be most satisfactorily explained by assuming a fault formed prior to the last caldera-subsidence.

V. D. BOSCH showed that there is a clearly marked dejection cone in front of the valley of Sapikerep and moreover that a corresponding shallow part in the adjoining Madoera strait may very well represent the submarine extension of this cone (bibl. 4—6). On this account he explains the formation of the valley of Sapikerep by the violent rush of water from a theoretical caldera-lake, formed after the first subsidence. In other respects his history of the Tengger corresponds to that of AKKERSDIJK.

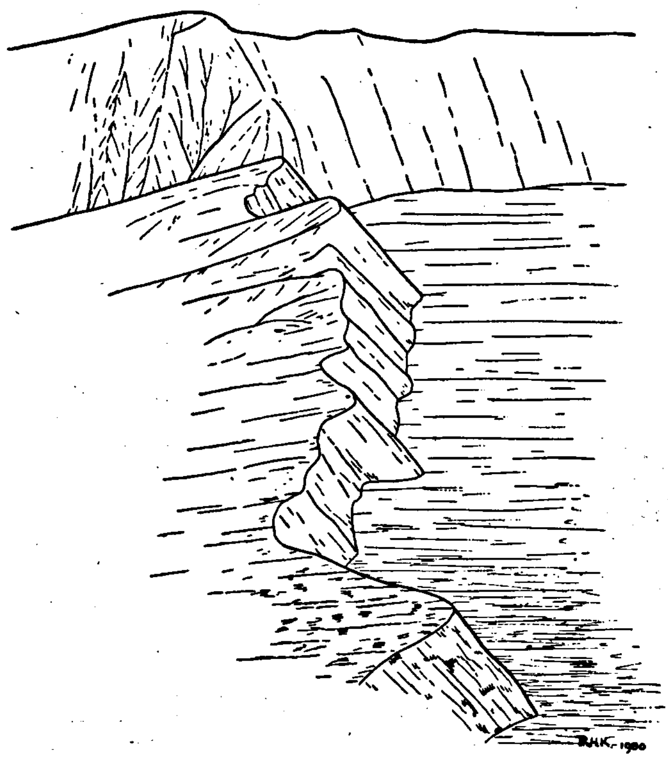

Fig. 9.

The Tjemoro Lawang seen from the Penandjahan; on the right the sandsea of the Tengger.

v. BEMMELEN, who accompanied AKKERSDIJK during the latter part of the fieldwork, and who made further observations later on, published a long article on the results. AKKERSDIJK's conclusions were confirmed and elaborated and may now be looked upon as a well founded conception (bibl. 3).

His principal reasons for rejecting the explanation of the valley of Sapikerep proposed by v. D. BOSCH are the presence of tuffs and lava flows of considerable thickness at the upper end of the dejection cone (the lower reaches were not examined). This cone can therefore also be explained as the lower end of the strato-volcano that filled the first caldera and the bottom of the valley. v. BEMMELEN also recalled AKKERSDIJK's observation that the southeastern slope of the first formed caldera and of the valley of Sapikerep are continuous, forming a straight steep precipice. This coincidence is more readily explained by assuming simultaneous subsidence than a separate mode of origin.

The geomorphological shapes of the Tjemoro Lawang can help to throw some light on the actual sequence of events. When viewing its forms from the Penandjahan, above the northwestern end, we are forced to assume that the bottom of the present N.E.-basin formerly extended a considerable distance beyond its present western limits. The shallow valleys that furrow its surface and drain off to the east have been beheaded by the cliff of the Tjemoro Lawang, the upper reaches having disappeared by collapse into the younger S.W.-caldera (fig. 9 and 10).

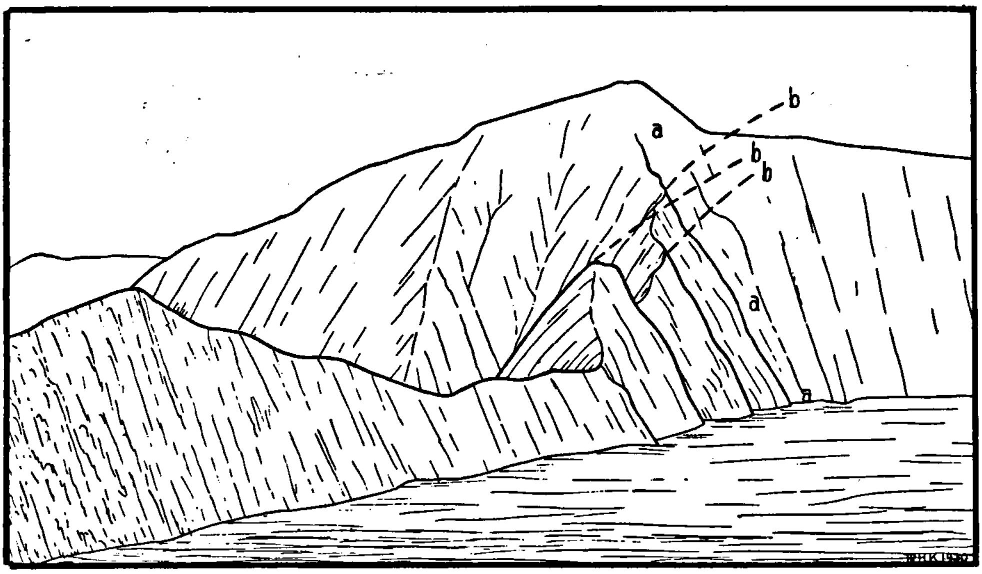

Fig. 10.

Southeastern end of the Tjemoro Lawang, seen from the sandsea of the Tengger; b = original surface.

The steep, caved-in slope of the Tjemoro Lawang is evidently a precipice that formerly extended to unknown depths below the present surface of the sand-sea; for no landslide material now rests in front of it, not even facing the identures in its course [1]).

How much further to the west the furrows in the N.E. basin formerly extended cannot be decided without detailed investigations, but it appears probable, that before the S.W.-depression was formed, the sloping bottom of the older depression reached to about the site of the Bromo.

[1]) At the northern end a young erosion gully has cut into the face of the cliff forming a delta in the sand sea, according to v. BEMMELEN.

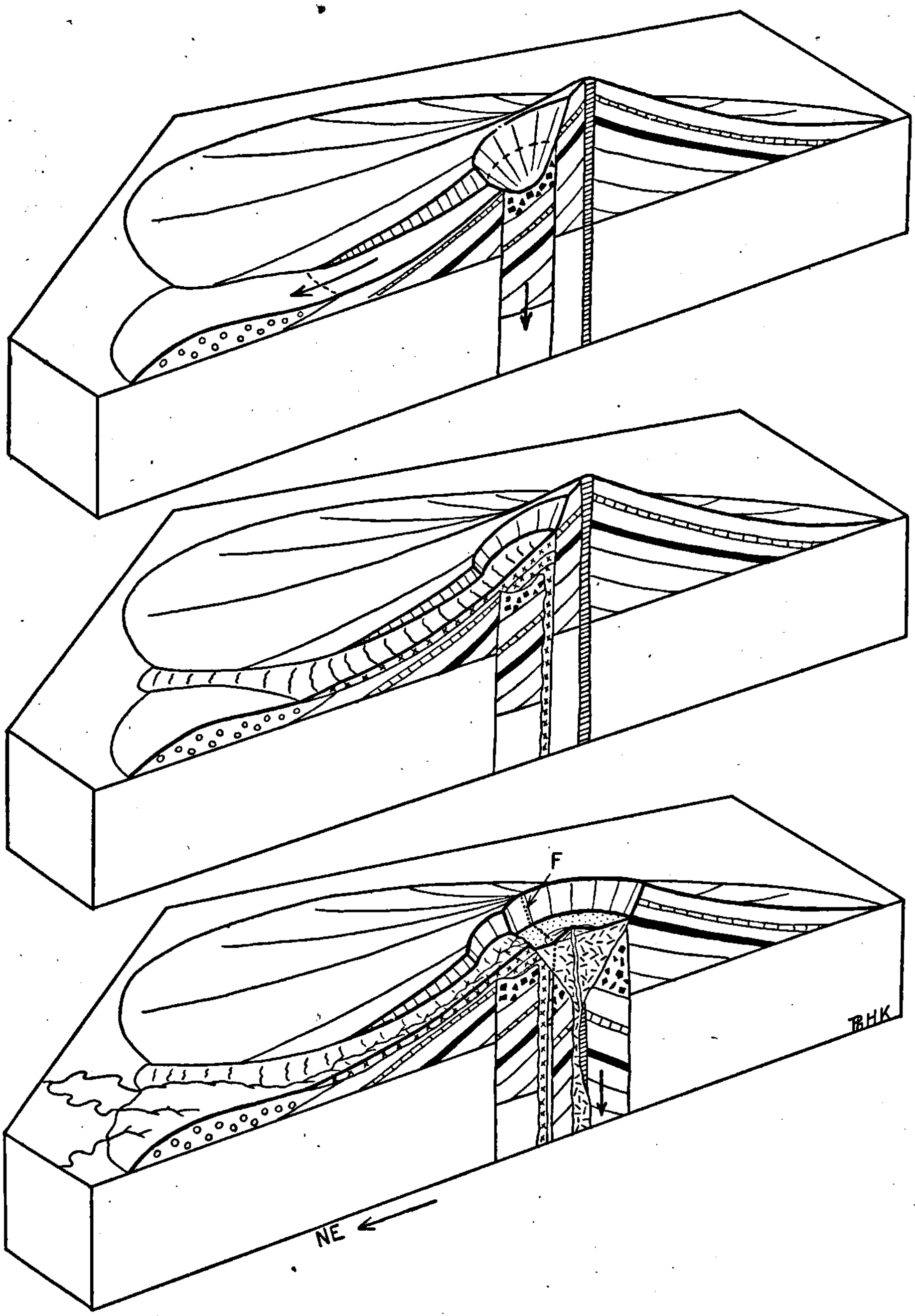

Fig. 11.

Blockdiagrams to illustrate the formation of the Tjemoro Lawang between the two calderas of the Tengger.
F = position of fault (?) causing the straight course of the cliff.

No lava ever flowed from the younger caldera to the N.E., for it would have effaced the shallow furrows. Evidently the present level of the sand-sea was reached by the rise of lava and the deposition of ash, covering up the rock that sank away from the front of the Tjemoro Lawang, after the formation of the S.W.-caldera. Viewed in this light it is more probable that the latter depression was formed by collapse along a pre-existing line of weakness (fault?) than by direct erosion during a gas-phase. This collapse may have taken place into a cored out funnel or directly into the magma chamber, either as a breccia or along a ring-dyke structure with subsequent superficial land slides, according to which theory on caldera-formation one holds.

Personally I prefer the last explanation on account of the investigations of the Scottish geologists. Violent extrusion of matter from the magma chamber may have caused decrease of pressure (not necessarily emptying of the upper part of the chamber) with the consequent sinking of the central block of a ring-dyke. The vertical walls of this cylinder above the plug immediately crumbled away until cliffs of 40° to 60° were left standing.

In the above indicated manner the morphology of the Tjemoro Lawang appears to confirm AKKERSDIJK's views on the history of the Tengger in so far as this feature is concerned. The feature that is responsible for the course of the Tjemoro Lawang must be situated some distance to the southwest of the cliff, below the sand sea (possibly continued in the walls of the younger caldera). For after the last caldera formed with a straight northeastern border, the top part crumbled away until a slope of about 40° was formed. A fault seems more probable than a dyke (F in fig. 11).

A few remarks must be added concerning the accompanying block diagrams: The formation of the caldera's is shown as the result of the ring-dyke mechanism, but for the sake of simplicity the dykes were not drawn in. Without whishing to adhere to the explanation for the valley of Sapikerep of either v. D. BOSCH or of AKKERSDIJK and v. BEMMELEN, the former was taken to show that a slight alteration may also be proposed, namely that a normal land slide took place (before the subsidence? (see page 297)).

When a detailed field investigation is undertaken this possibility might be taken into consideration.

The filling of the caldera's is drawn as if formed by solid lava as there was not sufficient space to represent stratified layers of lava and tuffs, a more probable supposition. Likewise the first caldera was filled by a strato-volcanic formation, as shown by AKKERSDIJK and v. BEMMELEN.

4. THE KLOET.

During the fourth Pacific Science Congres an excursion was made to the Kloet. The volcanological Survey had collected a large number of inclusions from the lava's for the visitors, one of which I examined in order to compare it to the inclusions of Paloeweh and Tidore. Miss KOOMANS kindly made an analysis of the rock and of the hornblende separately.

JUNGHUHN already pointed to the occurrence of inclusions in the Kloet-lava's and KEMMERLING investigated them; the latter found diorite and gabbro (bibl. 18).

The inclusion that I examined was a dark, coarse grained gabbro with clear feldspars together with a large amount of black hornblende and a little green augite. Under the microscope we see an allotriomorphic, holocrystalline mass consisting of the following minerals.

Plagioclase (85 %—95 % An, all four crystals measured twinned polysynthetically according to the Pericline law, with wedge-shaped laminae). Hornblende, pleochroïc light brownish-yellow to olive green, extinction angle 16°, Diopside, Magnetite. By micrometric analysis the following amounts were found:

plagioclase 59 %, hornblende 28 %, diopside 8 %, ore 5 %.

The analyses by Miss KOOMANS are as follows:

	Inclusion	Hornblende
SiO_2	41.07	39.42
TiO_2	1.11	1.78
P_2O_5	0.21	—
Al_2O_3	18.69	11.41
Fe_2O_3	8.39	6.65
FeO	2.81	5.43
MnO	0.16	—
MgO	7.53	14.96
CaO	15.36	15.27
Na_2O	2.17	2.94
K_2O	1.58	1.05
+ H_2O	0.85	0.84
— H_2O	0.12	—
	100.05	99.75

The chemical composition both of the inclusion and of the hornblende show a remarkable similarity to the unaltered basic inclusions of Paloeweh and the hornblende from that island as may be seen from the following table (ESENWEIN, bibl. 14).

	Kloet	Paloeweh 2243	Paloeweh 2219	Kl. hornblende	Paloeweh hornblendes	
si	81	82	85	67.5	72	75
al	22	21	22	11.5	14	13
fm	39.5	41.5	43	54.5	54	54
c	32.5	30.5	29.5	28	24.5	23
alk	6	7	5.5	6	7.5	10
k	0.33	0.20	0.11	0.19	0.14	0.19
mg	0.56	0.50	0.50	0.70	0.61	0.59
qz	—43	—46	—37	—56	—58	—65

This type of inclusion belongs to NIGGLI's pyroxenite-hornblendite magma, as ESENWEIN already pointed out, but the Kloet inclusion has a relatively high k-value.

5. SANGEAN (fig. 12—15).

At the northeastern corner of Soembawa a large active volcano rises

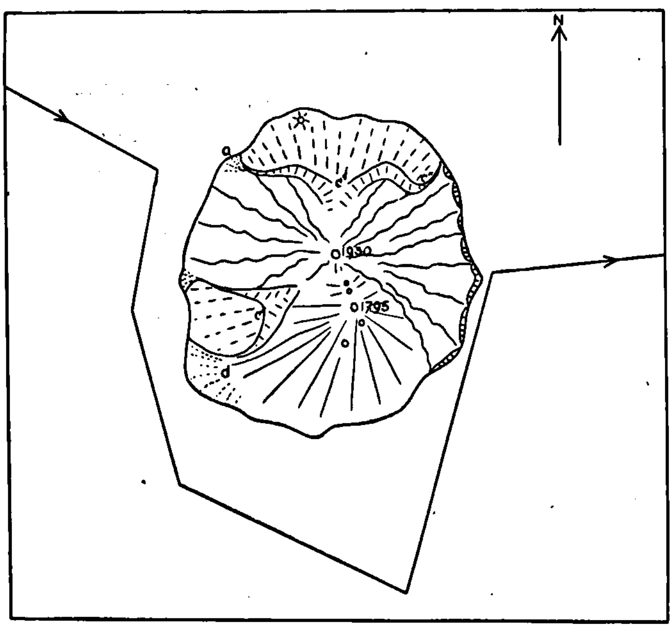

Fig. 12.

Sketch map of Sangean with the course of the Snellius, scale about 1 : 330.000.

from the sea floor to a height of nearly 2000 m, forming the volcanic island Sangean with the Goenoeng Api as highest summit (1930 m).

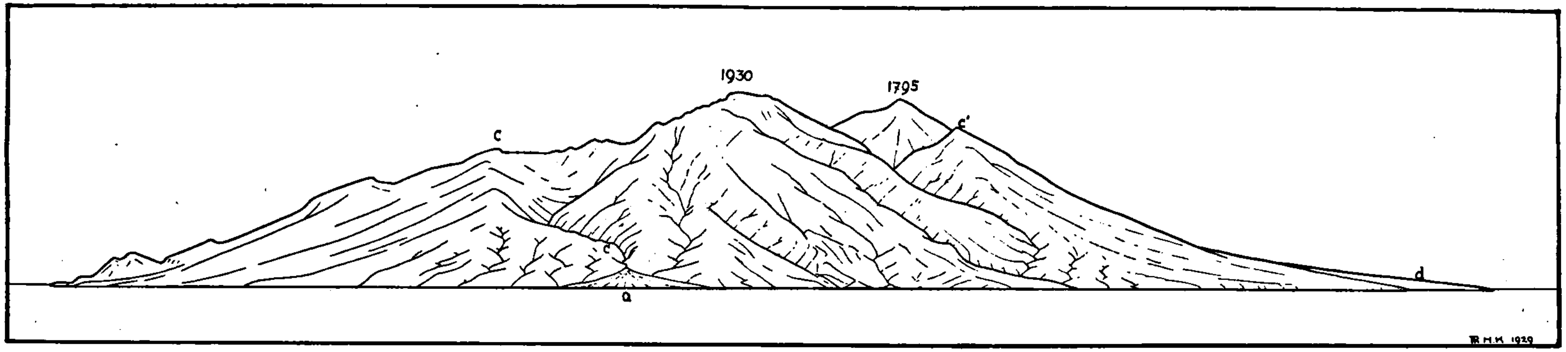

Fig. 13.
Sangean seen from the northwest.

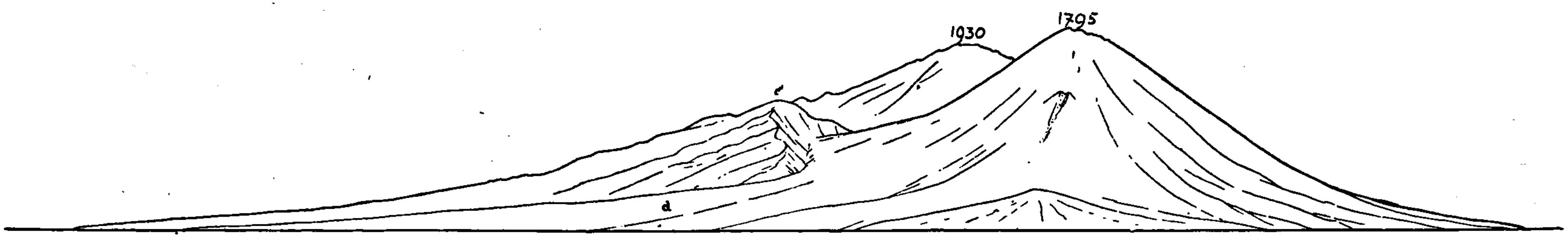

Fig. 14.
Sangean seen from the south southwest.

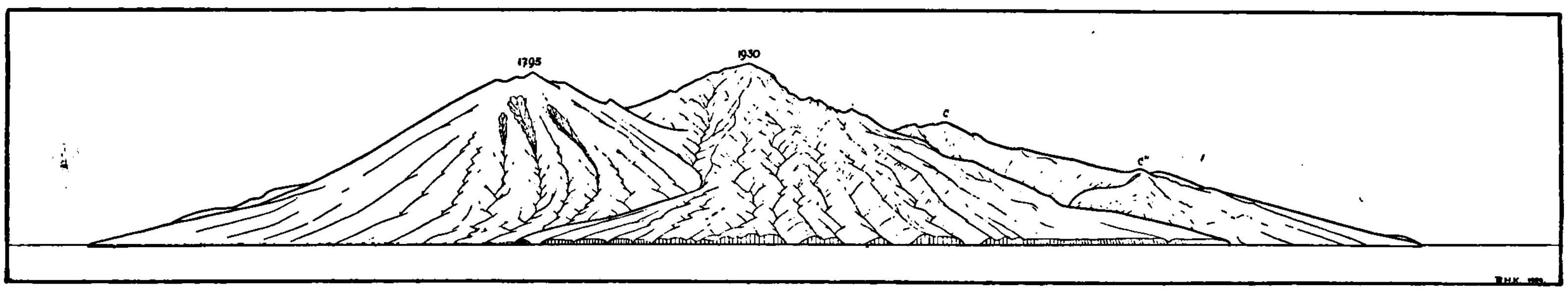

Fig. 15.
Sangean seen from the east.

Verbeek (bibl. 29) made two sketches while sailing past (fig. 43 and 44) and concluded that there was an old crater rim with a younger central volcano and a lateral eruption point in the south.

In 1927 Ehrat landed on the east coast and climbed the mountain (bibl. 12). His short report contains detailed maps of the craters with a description and a compilation of what is known concerning the eruptive history. Ehrat also describes the lava's that consist of andesites, with inclusions of diorite and granodiorite.

There is so little known yet about the major features of this group, that it is worth while to give the sketches I made while rounding the island on the south side. They had to be made somewhat hastily on account of the moving position of the expedition vessel and fig. 15 was drawn against the sun, sothat the light was very bad. The fig. 12 is a rough map made from these drawings, to show the relations of the various parts, but it only claims to be a general impression and the same appertains to the following remarks.

Two parts of an old crater rim appear from under the younger materials on the western and northern slopes (c, c′, c″). The Goenoeng Api lies in the centre of this caldera and its products reach the coast on the western and eastern shores. The deep erosion of the slopes and the cliffed shore at the east indicate that the surface is relatively old. The recent eruptions have not oblitterated this sculpture and have therefore not sufficed to cover the flanks of the cone.

The Doro Mantai (1795 m) lies some distance to the south and has been much less attacked by erosion. A few gullies are seen on the eastern side, but they have not cut back to the summit as yet and the coast is not cliffed.

Evidently this cone is of more recent construction, considered as a whole, than the Gn. Api. A minor crater is seen on the southern slope a little more than half way up.

At the northern coast a small young cone appears. The streams following the inner slopes of the old caldera have built delta's on the coast in consequence of their relatively large drainage area.

In my opinion the Doro Mantai is not situated outside the old caldera as Verbeek believed, but approximately on the rim, which it has entirely buried except towards the west.

6. PALOEWEH (fig. 16—18).

The volcanic island of Paloeweh has been recently described in some detail by Neumann van Padang (bibl. 25) who visited the island after the eruption of 1928. He mentions the formation of cliffed spur ends of the deeply serrated morphology (p. 20). On the contoured map accompanying his memoir they are not visible, however. My sketch, fig. 16, of a portion of the north coast shows these cliffs and what appeared from a distance as an ancient valley bottom, also notched, with consequent lowering of the erosion basis of the stream. The other sketch fig. 17, was made at a greater distance, some 5 km to the N.E.

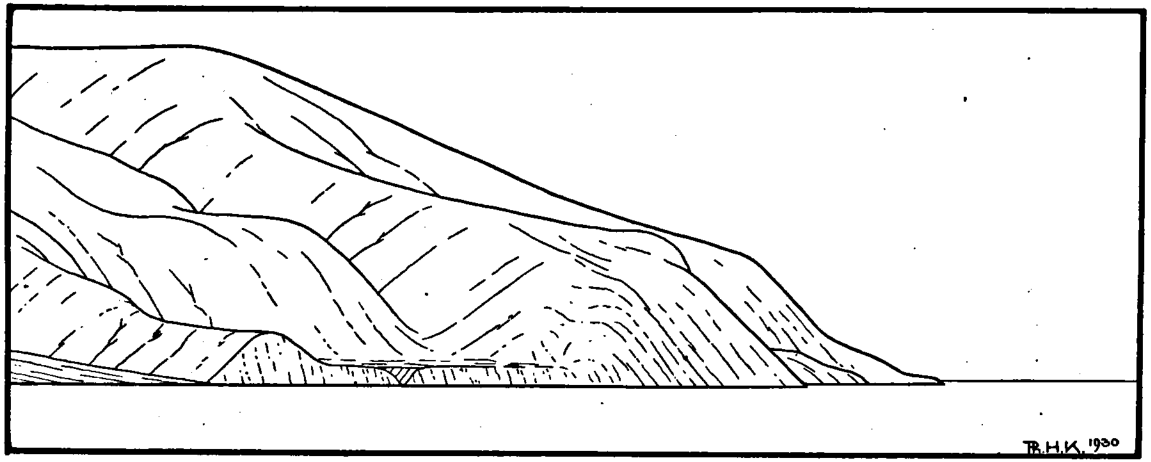

Fig. 16.

Portion of the north coast of Paloeweh.

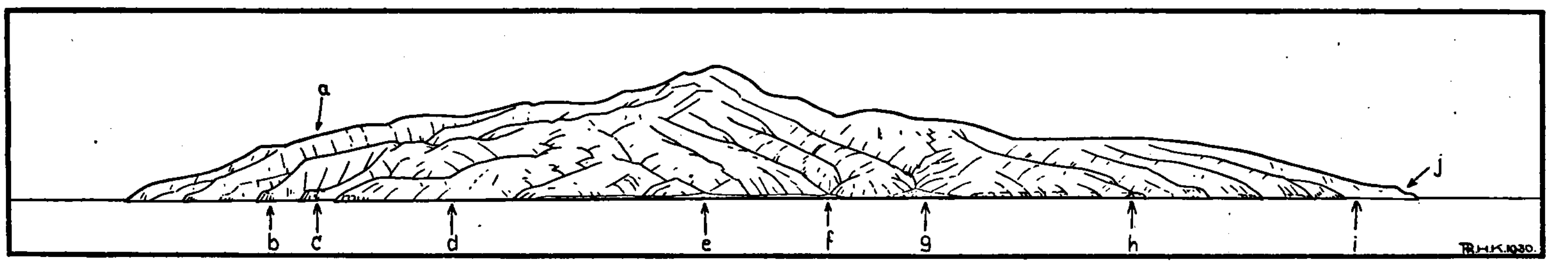

Fig. 17.

Paloeweh seen from the northeast.

of the island. On this drawing the havoc wraught by erosion on the slope of the volcano is brought out distinctly. The cliffed spur ends may also be seen. Besides the summit of the island, that is 875 m high, one may see the delta plain of Oewa(e), while the chief elements of the morphology can also be correlated with the map, probably as follows: a = ridge of Wadja; b = ridge north of Memeh; c = ridge west of Poa; d = ridge of Waiboie; f = valley east of Mage; g = valley between Mage and Oemaloee; h = Kaap Noord; i = Bay of Tomo; j = spur of Djawalo.

The soundings taken to the north show that corals and shells have slid down the slope to a depth of over 1000 meters (see bibl. 25,

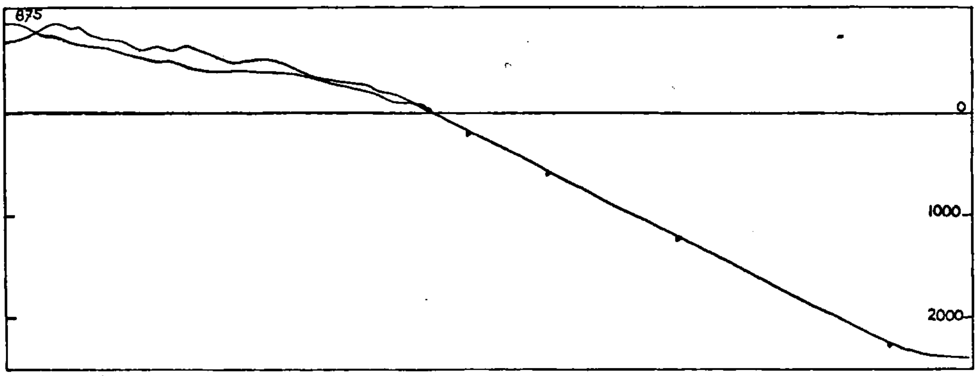

Fig. 18.

Section of Paloeweh, horizontal and vertical scale both 1 : 75.000.

p. 26—27). This is not surprising when the declivity of the slope is considered. Fig. 18 shows the two sections of the island appearing in the sketch fig. 17 and the slope based on a few wire-soundings and further out on echo-soundings true to scale. The submarine part is seen to be much steeper than the subaerial part. It is evidently built out in the manner of screes or the fore-set beds of a delta. Both subaerial erosion and excentral secondary eruption points have given the ruinous aspect and comparatively feeble slope to the emerging part of the cone.

7. GOENOENG API, NORTH OF WETAR (fig. 19—21).

The small volcanic island Gn. Api was visited in 1899 by VERBEEK, who described it as a simple cone, with a breached crater on the southwestern side in solfataric action, and built un principally of lava. No eruptions have been reported (bibl. 29, p. 570—572).

The island is densely populated by enormous flocks of sea birds and covered with brushwood. During our visit of a few hours, only weak solfataric action was observed. As some earth had formed even on the youngest lava flow, the last eruption must have taken place a considerable time ago. The flourishing reefs on various parts of the coast and the abrasion cliffs that rise to 20 or 30 m along most of the circumference point in the same direction.

Although the cone rises only 282 m above sea level it is nevertheless

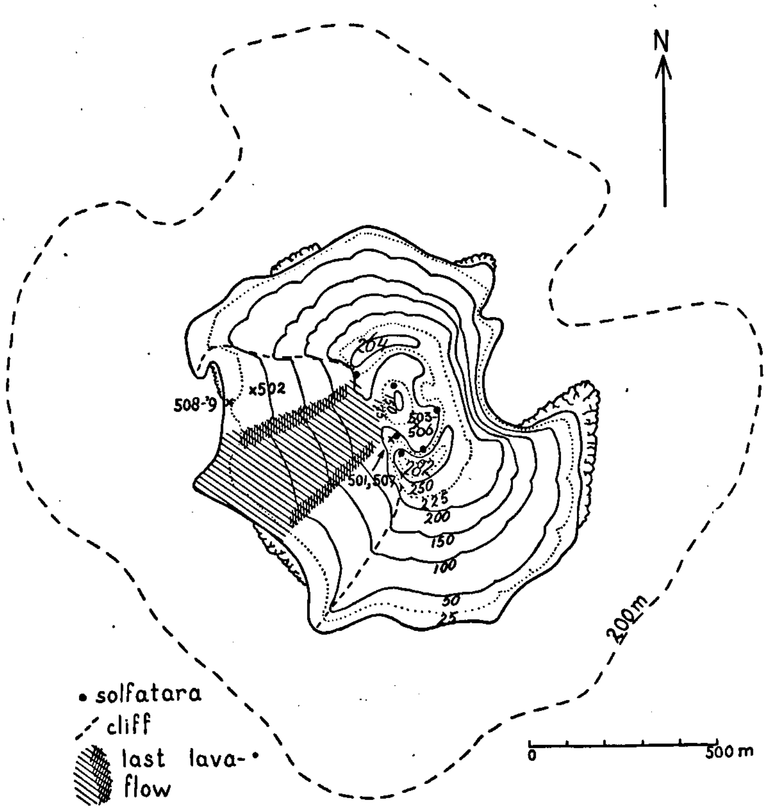

Fig. 19.

Sketch map of Gn. Api north of Wetar, scale 1 : 20.000; contours only roughly estimated.

one of the highest, perhaps the highest volcano of the entire East Indian Archipelago. The echosoundings in the surroundings prove that this volcano rises up near on 5000 m above its original base! The data are insufficient to decide whether it rests on a flat part of the sea floor or on a slight elevation (see bibl. 22, fig. 27, p. 64).

Since the cone reached its present height three great landslides have taken place. One on the northwest side is only indicated by an indenture of the 200 m-line. The one on the east side has carried away a considerable part of the slope above sealevel and reached down below the 200 m-line, that shows a deep bay. The fact that this slide has a vertical range of about 500 m and lies partly below sealevel proves that

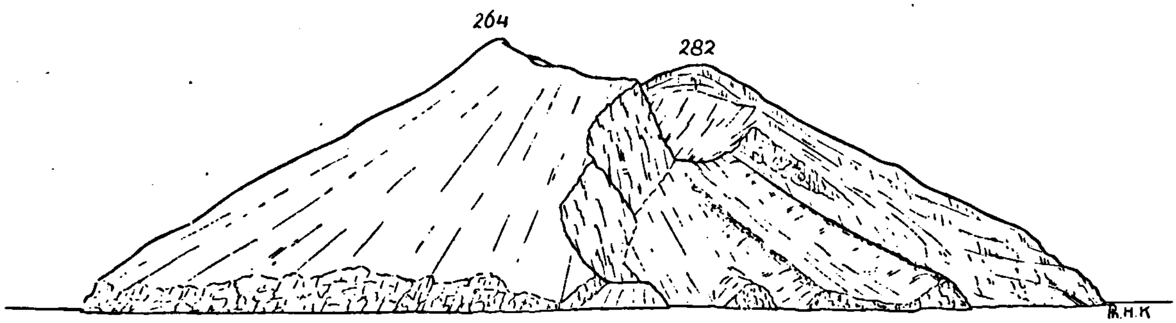

Fig. 20.

Gn. Api seen from the west.

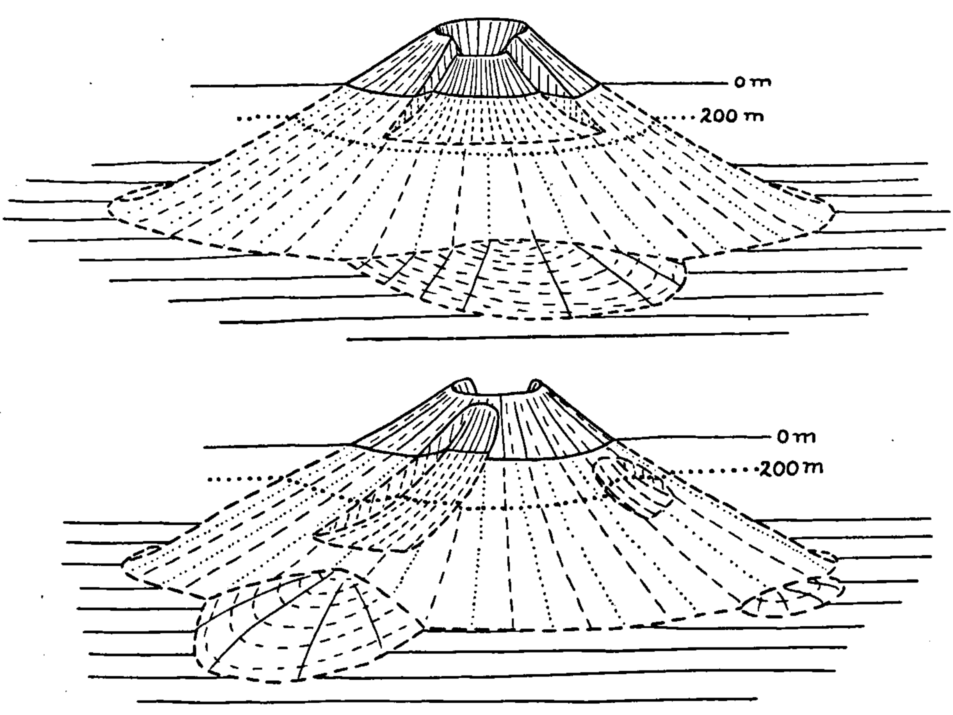

Fig. 21.

Blockdiagrams illustrating slides on Gn. Api, one of which opened the crater.

it took place at one single time and not in a succession of small local crumblings. As a reef grows partly inside the area of the slide, the movement must have occurred some time ago and the bareness of the slope must be attributed not so much to youth as to steepness of the slope.

The third slide took place on the west side and carried down a sector of 90°, reaching from the crater to some way below sealevel. As the 200 m-line is undisturbed, the slide does not reach as far as this depth and the materials were shed further down the slope (see fig. 21 in which the height of the cone is greatly reduced). The thickness of the missing part is some 50 meters. It can be seen on the steep cliffs along the sides of the slide that the missing part consisted of thick lava beds with thin layers of tuff intercallated.

As two of the three slides did not affect the crater rim it seems improbable that water or lava in the vent played a part in forcing away the sectors. This conclusion is of some moment as the pressure of lava or water is often invoked to explain the breaches in crater rims of volcanoes. Evidently the steep slopes and stratified nature of a volcanic cone are sufficient causes for producing large landslides (see page 288).

Since the slide took place in the west two lava flows have come down the breach. The first consists of slaggy lava and is exposed on the coast on the north side (hand specimens 508, 509). The second flow is formed of black, andesitic block lava. After the exterior had consolidated the inner part broke through at the lower end and flowed into the sea, forming the projecting cape. The consolidated sides of the flow stand out as ridges some 6 m from the slope. The surface is slightly concave.

Solfataric action was observed at 5 points in the crater. There was also a pit some 40 m deep inside the rim formed by the upper end of the young lava flow. On the eastern side a partly destroyed dome could be observed (held by VERBEEK to be a small eruption cone).

Petrography.

VERBEEK (p. 652) described two samples of lava from the north coast. Both are fine grained pyroxene andesites, with phenocrysts of plagioclase, hypersthene, augite, biotite and olivine containing picotite, magnetite and apatite; the microlitic groundmass consists of pyroxene, plagioclase and ore in colourless or brown glass.

My own samples (501—509) were obtained from the crater and the west coast. They are all pyroxene basalts with the same minerals as VERBEEK found. The handspecimens vary from light to dark grey or reddish colours; they are mostly porous and show white and dark phenocrysts of a few mm. The relative amounts vary considerably. Thus one sample (506) was comparatively rich in olivine, while in the others it only forms part of small inclusions together with some plagioclase, pyroxene and ore. Sometimes the hypersthene predominates over the augite, sometimes it is the other way about. The biotite is generally an accidental component.

These variations are most obvious in a conglomerate tuff (502) showing almost as many types as there are inclusions in the slide.

The plagioclase is rich in inclusions and is idiomorphic and zonal.

The composition varies from 60 % to 80 % An (18 determinations with U. St.), in a single crystal the zones sometimes show differences of 12 %.

The groundmass shows the same minerals occurring as phenocrysts and sometimes countless rod-shaped crystallites. The amount of glass is on the whole not great.

Miss KOOMANS analysed one sample (508) with the following results:

Gn. Api	508	Seroea 495		508	495
SiO_2	56.23	57.29	si =	165	165
TiO_2	0.35	0.64	al =	32	27.5
P_2O_5	0.39	0.21	fm =	30	40
Al_2O_3	18.66	16.35	c =	25	25
Fe_2O_3	3.80	5.54	alk =	13	7.5
FeO	2.43	2.07			
MnO	0.11	0.16			
MgO	3.39	5.24	k =	0.38	0.29
CaO	7.89	8.06	mg =	0.50	0.56
Na_2O	2.89	1.88	c/fm =	0.83	0.62
K_2O	2.76	1.12	qz =	+ 13	+ 35
+ H_2O	1.03	1.05			
— H_2O	0.16	0.40			
	100.09	100.01			

A micrometric analysis of 508 gave the following mode:

Plagioclase	28 %
Augite	5 %
Hypersthene	4 %
Olivine	4 %
Ore	2 %
Biotite	0.3 %
Groundmass	56 %

The magma belongs to NIGGLI's normal dioritic magma, with a tendency towards the tonalitic magma.

8. SEROEA (fig. 22—25).

Little is known of this volcanic island. It was paid a short visit in 1899 by VERBEEK (bibl. 29, p. 577—578, fig. 500—502). He believed it to consist of a large and small cone, situated within a rim of older lava and breccia's. The large cone showed solfataric activity and appeared to posses a crater filled with blocks of lava. Two lava flows, directed towards the east, he believed to be young: one he even thought might be ascribed to the last eruption (1687, 1693, 1844).

I landed on the north coast and gained the summit by way of Lesloeroe, but there was no time to make a detailed survey. The con-

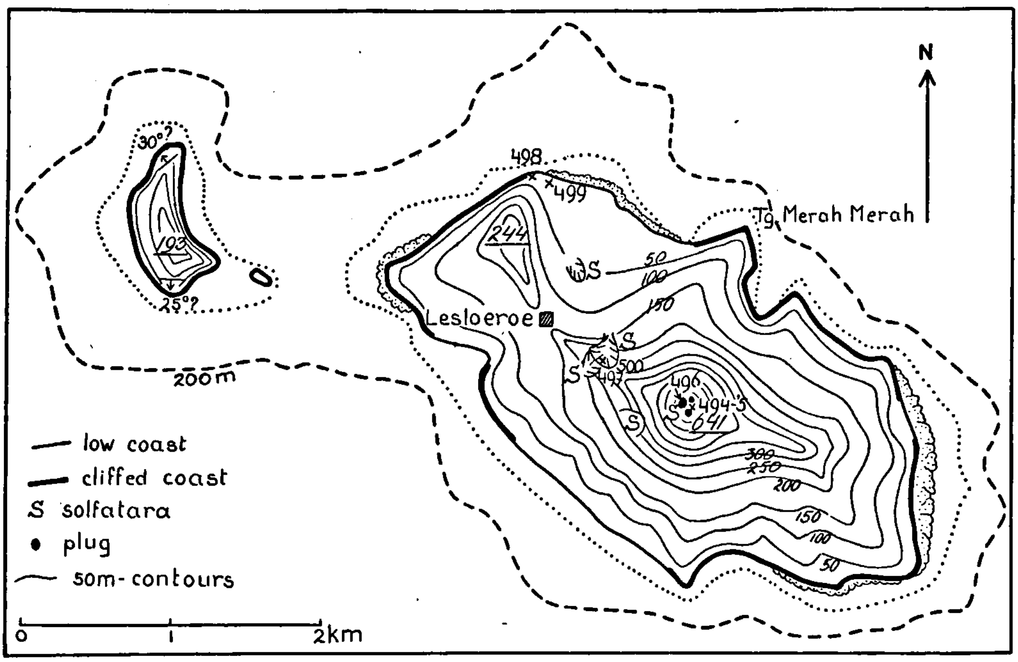

Fig. 22.

Sketch map of Seroea and Kekeh, scale 1 : 50.000; contours roughly estimated.

tours on the map are only a rough estimate of the general configuration.

The island appears to be built up of a relatively large proportion of lava, that must have moved down the slopes in viscous flows.

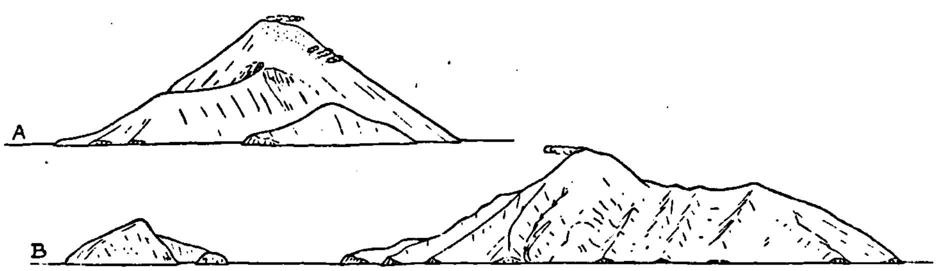

Fig. 23.

A = Seroea seen from the northwest. B = Seroea seen from the south.

On the whole it is porous and crumbly. At the summit two, probably three, small lava plugs were found close together. The smallest one, at the north, presented a curved surface on one side, formed by the highly viscous flow of the lava out of the vent. Its size was estimated at 10 by 10 m. The largest plug, at the southwest was about 10 m high and 40 m broad, and must have been formed by a somewhat more mobile lava, that was able to flow a short distance down the slope. To the southeast a bulge occurs that probably also represents a small plug.

Besides the lava's a subordinate amount of (breadcrust) bombs, conglomerate tuffs and ash containing coarse pumice were observed.

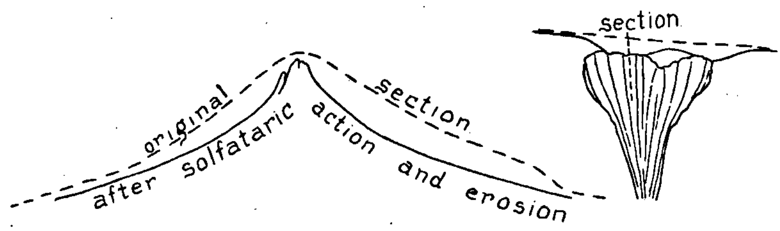

Fig. 24.

Section and side view of solfatara-field to the southeast of Lesloeroe on Seroea.

Solfataric action plays an important part in the present stage of activity. Two active and two dormant fields were found. At the summit of the volcano the activity is considerable, all rocks except the domes being crumbly and decomposed. A second active field with 4 or 5 solfatara's lies at an altitude of 300—400 m on the southwest slope. One dormant field, due north of Lesloeroe at an altitude of about 80 m is small, the other occurs between this village and the summit reaching down on both sides of the ridge from some 300 to about 200 m and covering an area of two hectare's. In both fields erosion has carved deep into the crumbly rocks. VERBEEK's opinion that a second cone is to be found here proved to be wrong.

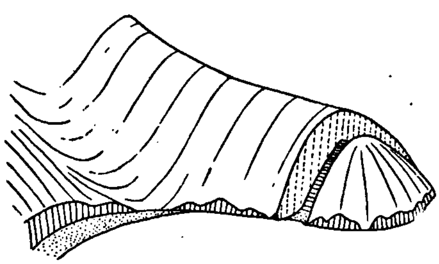

Fig. 25.

Blockdiagram showing abortive slide on the north cape of Seroea.

I could find no support of VERBEEK's statement, that young lava flows occur on the northeast slope. As far as could be ascertained from a distance the projecting capes are cliffed by abrasion, and cannot be very young. This abrasion would account, however, for the fresh appearance of the rock mentioned by VERBEEK.

The accurate chart of the group made by the Hydrographical Survey, together with my own observations show that the general shape is more oblong than VERBEEK believed. There does not appear to be an „older rim'' around a „younger cone'' but a northwest to southeast row of eruption points one of which has been built up to the present central cone. The two Kekeh's probably belong to a partly destroyed, small cone: the most westerly of the row.

A curious morphological detail may be seen at the northwestern cape of the chief island. This cape is crossed by a fairly deep gorge that must be ascribed to an abortive slide of the extreme end of the mass (see fig. 25).

Petrography.

Verbeek (p. 654) described a pyroxene andesite lava from the northwestern coast, with hypersthene and augite and an olivine bearing pyroxene andesite from the east coast (probably Tg. Merah Merah?).

My own slides (nos. 494—500) do not contain olivine and all belong to rocks similar to those described by Verbeek. There is, however, considerable variation in relative amounts of all phenocrysts and of the groundmass. The analysis of 495 is given on p. 298. The magma is tonalitic-peléeitic, with low alk.

With the universal stage the smaller phenocrysts were found to contain 75 %—80 % An (4 determinations), the larger ones in the centre 85 %—90 % and a few % less towards the margin (2 determinations).

In the handspecimens the rocks are porous, one even pumice-like, varying in colour from blackish grey to light yellow.

9. TIDORE (fig. 26—32).

A. Former investigations.

Tidore is a volcanic island situated to the west of Halmahera and to the southeast of Ternate. No historic eruptions have been reported from this island.

The first geologist to pay Tidore a visit was again Verbeek (bibl. 29, p. 144—146 and 250—251, fig. 126—129, 132). Besides a short description of some specimens collected, Verbeek gave a few sketches taken at a distance from various directions. Verbeek concluded to the existence of 4 separate eruptions points. In the north a small collapsed cone is followed on its southern flank by a cone with well preserved conical shape, then a larger cone with three summits, two of which belong to an older crater rim. The entire southern portion of the island is occupied by the highly symmetrical and excellently preserved volcano of the Piek van Tidore. A small crater at the summit is breached on the northwestern side.

Verbeek landed on the east coast in the bay of Akisahoe. He observed a warm spring welling up out of andesite near the shore. He was also able to study two sections, one consisting of greyish-yellow tuff, the other of a succession of tuffs with pumice and pyroxene andesite, wheathered mica andesite with hornblende and a lava flow of

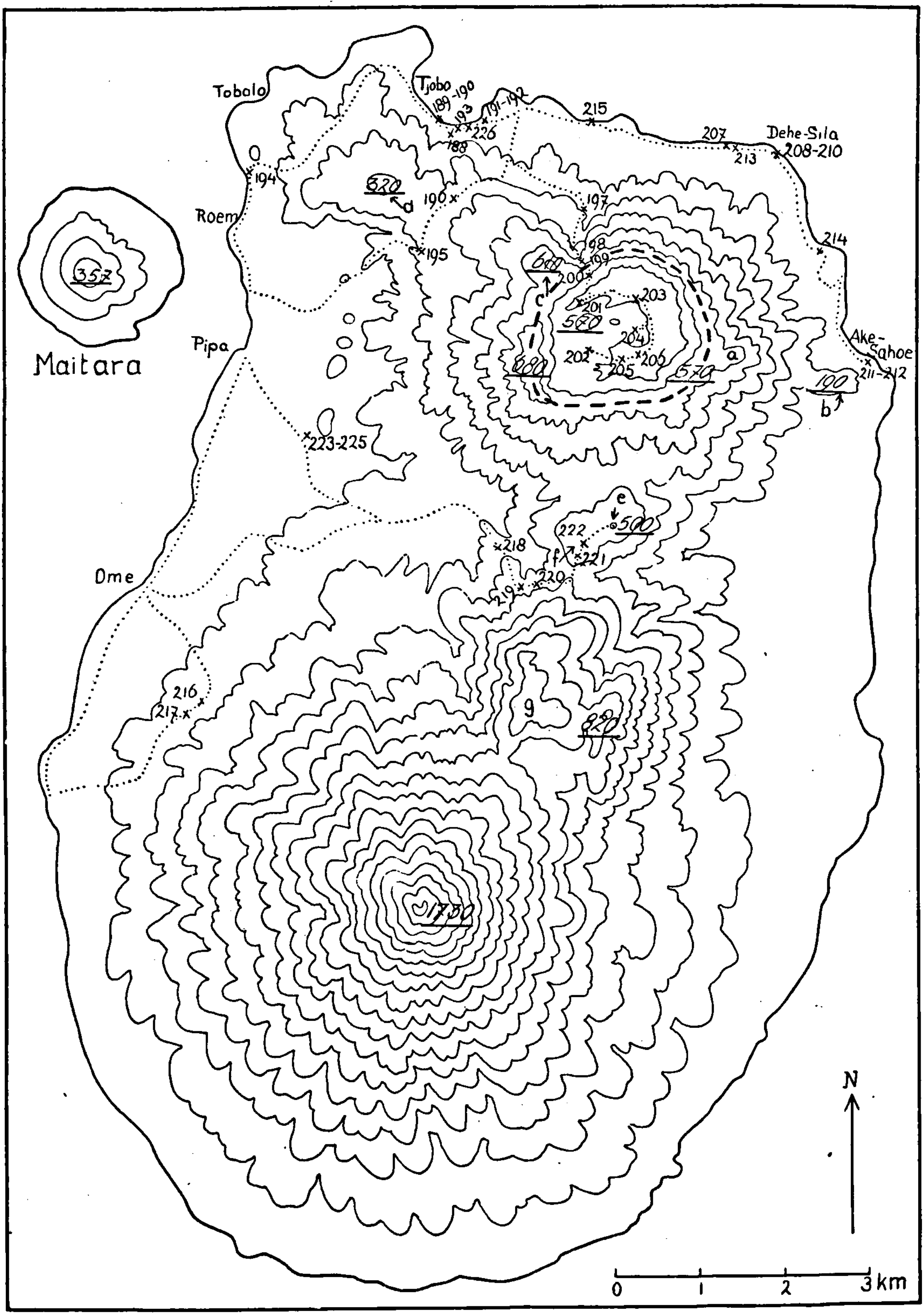

Fig. 26.

Map of Tidore, after sketch map by the Topographical Survey, scale 1 : 75.000.

olivine bearing pyroxene andesite. All products had come from the northern eruption point. On the coast at Selli an exposure of the southern cone was examined, where a lava flow of dark grey, porous pyroxene andesite occurred. The mountain is composed mainly of loose ejectamenta. VERBEEK also drew attention to a description of two pyroxene andesites from the chief volcano, described by RETGERS in 1895 (bibl. 27).

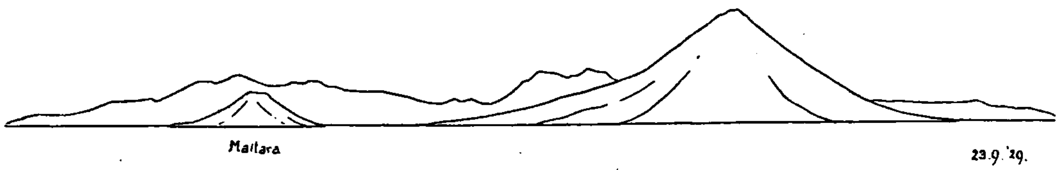

Fig. 27.

Tidore and Maitara seen from the west.

B. Geology.

My stay on Tidore lasted 5 days. Besides to make observations on coral reefs, I was able to visit the northwestern part of the central and the northwestern foot of the southern eruption points. Owing to illness a projected excursion to the southeastern section of the island at a later occasion had to be given up. An excellent contoured sketch map by the Topographical Survey materially aided the field work.

VERBEEK's surmise of the existence of 4 eruption centres could be confirmed in the main lines.

In the north lies a cone of about 600 m with a large crater which is about 150—200 m deep with a flat marshy floor. The diameter approaches 2 km. Three small separate cones have arisen in a row on the western side of the bottom of the crater.

The floor of the crater consists of brown earth with many nuggets of obsidian, partly massive, sometimes with devitrification, partly porous. On the north side of Boekoe Maitara there occurs a lava flow of obsidian, on the southern flank andesite was found in the tuffaceous slope. It may represent an inclusion derived from the substratum. At the foot of the central hill andesite was exposed. This seems to indicate that after the eruption of the obsidian as bombs and lava flows, together with volcanic ash, an andesite extrusion closed the volcanic cycle.

Besides the main cone just described, the northern part of the island contains several secondary eruption points. On the southeastern slope there are Pakai Maboehoe (*a*) and Soepera Maoegoe (*b*), on the northwestern side Kota Moem (*c*) and Boekoe Gambir (*d*). The general shape of the bay of Tobala suggested to me, at the time of my visit, a wide crater, but this surmise is doubtfull. The points mentioned lie on a fairly straight line running from Soepera Maoegoe, through the secondary cones in the crater to Tobalo (see fig. 26 and 32). It should be noted that the bay of Tjobo is probably not a crater, but a submerged valley.

VERBEEK's second cone consists of two separate rounded hills, the Boekoe Foeloeloe (*e*) and the Boekoe Goelili (*f*), that are — it is true — so close together as to form one mass, but nevertheless quite distinct from one another. They are more or less dome-shaped and in all likelihood consist of a twin lava plug (one might almost speak of a „Siamese twin").

VERBEEK's third cone (*g*) I was not able to visit. The map shows two parallel ridges running north to south, connected by another. Owing to clouds not much was visible from the north at the time I was there. Judging by the little I was able to make out through the shifting cap of clouds (fig. 31), there must be a fairly complicated set of spurs and probably also at least one lava plug.

Concerning VERBEEK's fourth eruption point, the Piek of Tidore, I have no new observations to add.

VERBEEK attempted to solve the problem of the relative ages of the various volcanoes by noting the degree of erosion. The question cannot, however, be solved in this simple manner, as the superficial strata differ too widely in composition to allow of a direct comparison. A thick deposit of fine, loosely heaped pumice-breccia formerly coated the slopes of the northern cone. A thin skin of sandy, pisolitic tuff, considerably harder, covered this mass up giving rise to curious erosion forms and deeply serrated slopes.

Fig. 29 represents a sketch of the outer slope of the northern cone seen from the southwest. The erosion indicated must have occurred since the formation of the crater, as the valleys do not cut through the crater rim, but start a small distance down the slope. For this reason I believe that the formation of the large crater was accompanied by a great eruption of ash and pumice, a combination of phenomena often encountered.

Fig. 28.
Tidore seen from the anchorage of Ternate.

Only in the deeper valleys and along the coast do the andesito-

Fig. 29.

Deeply serrated covering of tuff on the southwestern slope of the northern cone of Tidore.

basaltic breccia's and lavas appear from beneath the covering of loose

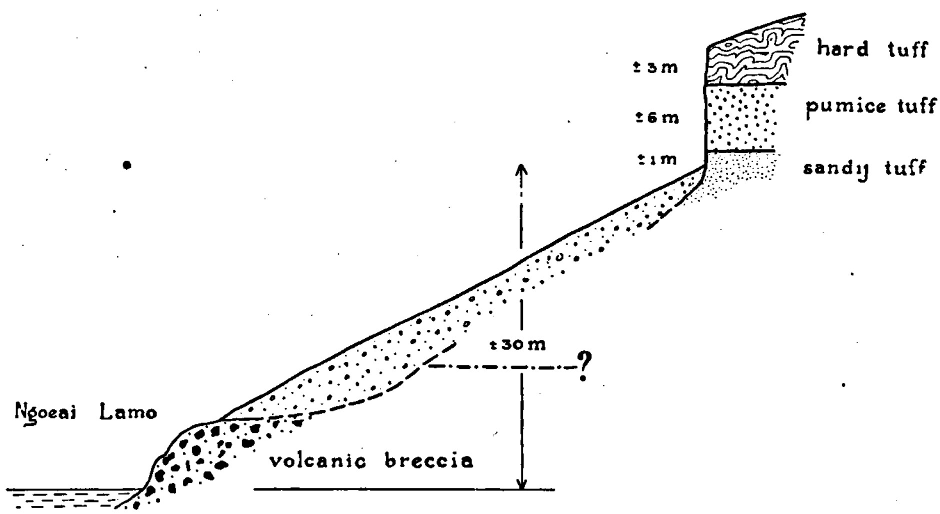

Fig. 30.

Section of tuff west of the northern cone of Tidore (handspecimen 223—225).

materials. The lava flows are thin, between 1 and 2 meters where I could study them (north of Mafkoko).

At Mafoegoja deep gullies have been washed out with vertical walls, comparable in shape, though not in size, to the famous canyon of the Karbouwen gat near Padang on Sumatra.

To the east of Pipa a curious cuesta-like landscape forms the lower reaches of the slope. In the Ngoeai Lamo the following section was visible. Andesito-basaltic conglomerate tuff, covered by a soft sandy tuff, followed by 6 meters of loosely heaped pumice of from pea- to orange-sized, rounded pieces. On top came a thick layer (at least 3 m) of hard sandy tuff (fig. 30).

The cuesta in my opinion owes its formation to the ease with which the lower tuff's are attacked by erosion. The covering tuff is

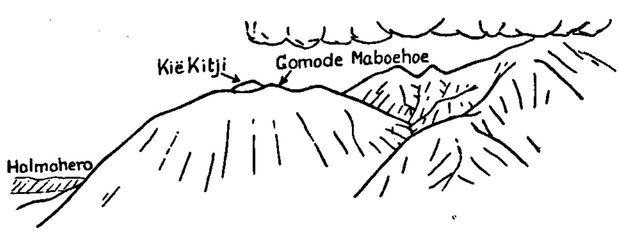

Fig. 31.

The third eruption point of Verbeek on Tidore seen from the north.

much firmer and thus protected the substratum. Geologically speaking the cuesta landscape will very soon have disappeared as even the protecting stratum is a crumbly, soft and thin layer.

On the central cones the pumice is also present and obsidian occurs as loose ejectamenta (probably derived from the later eruptions of the northern crater?). The main cone appears to be free of both rocks. This might indicate that more recent products were shed on the southern cone since the extrusions of the northern volcano ceased. On the other hand the flanks of this mountain have been considerably attacked by erosion, although the materials are firmer, consisting of lava's and tuffs.

Without further information the age problem is therefore difficult to solve. The writer is inclined to consider the truncation of the northern cone together with the deposition of the pumice and soft tuffs and the subsequent small events mentioned above, as the last manifestation of volcanic activity on Tidore.

C. Petrography.

The rocks of Tidore cover a fairly wide range of basalts and andesites, varying from 50 %—70 % SiO_2.

Retgers (bibl. 27) and Verbeek (bibl. 29) described pyroxene andesites almost without olivine and with a glassy groundmass from Tidore. Verbeek also found andesitic tuffs and a tuff with mica andesite; but the latter was lost before it was properly examined.

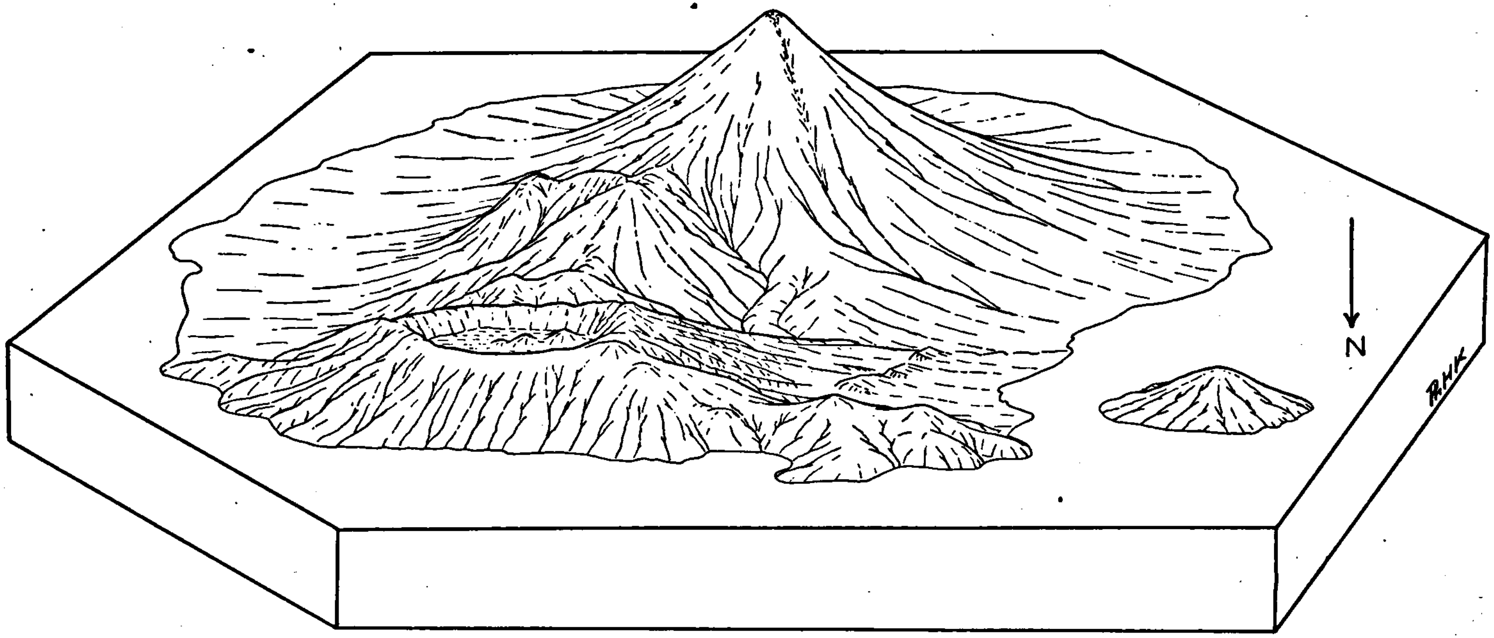

Fig. 32.

Blockdiagram of Tidore and Maitara seen from the north.

From the neighbouring volcanic islands VERBEEK mentions basalts and also hornblende andesites.

The following description is based on 30 slides and handspecimens. With the U. St. 110 determinations of plagioclases were made, of which 10 by the Fedorof-Reinhard and 100 by the zone extinction method. The latter method gave on the whole about 5 % more An in the same slide.

Besides the tuffs six groups of rocks can be distinguished.

1. *Basic basalts* (188 analysis, 197). Dark grey rocks. The phenocrysts consist of plagioclase with 70 %—90 % An, olivine, augite and ore. The groundmass consists of glass with small crystals of the same kinds as the phenocrysts.

2. *Intermediate basalts* (191 analysis, 192, 193, 194, 198, 199, 200, 202, 216, 217). Light to dark grey or purplish rocks. The phenocrysts consist of plagioclase (50 %—80 % An, mostly about 60 %), olivine, augite, hypersthene (sometimes only in the groundmass) ore and reddish brown hornblende in small amounts (absent in 200, 216, 217). The groundmass contains the same minerals in a glassy matrix.

3. *Andesitic basalts* (207, 208, 209, 211). Light to dark grey, purplish rocks. The phenocrysts consist of plagioclase (60 %—75 % An), augite, hypersthene and ore. Hornblende only occurs in 211. The groundmass consists of devitrified glass with plagioclase, ore and microlites.

4. *Basaltic andesites* (218 analysis, 219, 219*a*, 220, 221). Pink or yellow rocks, sometimes with fluxion structure. The phenocrysts consist of plagioclase (45 %—70 % An, mostly about 50 %), hypersthene, ore and hornblende. One sample, 219*a*, contains a few grains of olivine. The groundmass originally consisted of glass with small crystals and crystallites but is now devitrified in most slides.

5. *Vitro andesites* (201 analysis, 203, 204, 206, 222). Black or grey, vitreous rocks. The rare phenocrysts consist of plagioclase (40 %—65 % An, mostly somewhat less than 50 % An) and hypersthene, and in one rock (204) a fair amount of greenish-brown hornblende. The black, glassy base is crowded with crystallites.

6. *Basic inclusions* (191*b* analysis, 193*b*, 220*b*). Purple or grey rocks. The phenocrysts consist of plagioclase (55 %—95 %, mostly 70 %—80 % An) and reddish brown hornblende. Two inclusions from intermediate basalts (191 and 193) contain olivine, the former with hypersthene, the latter with augite and with hypersthene in the groundmass. The third inclusion from basaltic andesite contains both hypersthene and augite but no olivine. All three have a glassy, porous groundmass with small crystals. From the fact that they vary in composition according to the enclosing rock, it follows that they were formed shortly before the consolidation of the lava as local concretions of minerals and do not represent parts of deepseated, differentiated magma. The fine grain, porphyric structure and glassy matrix are in accordance with this view. Further evidence is given in the chapter on petrology.

Various tuffaceous rocks have already been mentioned. One of these needs special attention. In the cliff near Akesahoe, where VERBEEK already found tuffs, I observed a curious, yellow, sandy rock with complicated but unmistakable fluxion structure. As this rock also contained small spherules I took it for a devitrified odsidian. However, a similar rock from close by showed inclusions of pumice and andesite and the microscopic investigation bore out the tuff-nature of all these rocks. The spherules must therefore be of pisolitic nature (bibl. 23, p. 419—421) and the fluxion structure can only be explained by muddy flow of wet ash shortly after it fell.

The following analyses were made by Miss KOOMANS:

	188	191	191 inclusion	218	201	incl. calculated
SiO_2	49.89	57.73	51.18	68.37	70.44	51.0
TiO_2	0.95	0.72	0.84	trace	0.02	1.2
P_2O_5	0.16	0.14	0.10	0.12	0.16	0.1
Al_2O_3	19.26	15.97	14.75	13.51	15.63	14.5
Fe_2O_3	5.72	6.42	7.98	3.09	1.94	9.6 (Fe₂O₃ + FeO)
FeO	4.56	0.98	1.11	0.61	1.13	
MnO	0.13	0.09	0.12	0.04	0.07	0.1
MgO	5.33	5.09	10.49	0.77	0.56	8.1
CaO	10.11	7.05	8.55	3.55	2.36	9.4
Na_2O	1.48	3.13	1.81	5.20	4.61	3.4
K_2O	1.90	1.75	1.73	2.69	2.95	1.6
$+ H_2O$	0.46	0.63	0.88	1.63	0.37	0.7
$- H_2O$	0.12	0.39	0.34	0.40	0.02	0.2
	100.07	100.09	99.88	99.98	100.26	99.9
si	121.5	168	118	302.5	330	
al	27.5	27.5	20	35.5	43	
fm	39.5	38.5	52.5	16.5	15.5	
c	26.5	22	21	18	12	
alk	6.5	12	6.5	30	29.5	
ti	2.2	1.93	1.80	—	—	
p	0.15	0.18	0.14	0.27	0.28	
h	4.7	10.0	9.4	30	6.2	
k	0.45	0.27	0.38	0.26	0.30	
mg	0.49	0.57	0.69	0.28	0.25	
c/fm	0.67	0.57	0.40	1.09	0.76	
qz	—4.5	+ 20	—8	+ 82.5	+ 112	

No. 201, vitro andesite, belongs to NIGGLI's trondhjemitic magma. No. 218, basaltic andesite has a plagioclase-granitic composition, but on account of the low al and high alk the difference between these two is very small. No. 191, intermediate basalt, has a normal-dioritic composition. No. 188, basic basalt, is of sommaite-diorite composition, but alk is low. The inclusion, no. 191, has a normal gabbroidic composition, but as k is 0.38 there is a tendency towards the sommaite-dioritic magma.

Micrometric analyses:

	201	218	191	188	191 inclusion
plagioclase	3	6	24	27	13
pyroxene	0.25	0.6	7	11	tr.
olivine	—	—		9	6
hornblende	—	2	5	—	31
magnetite	0.1	0.2	tr.	1	—
groundmass	96.6	91	64	52	50

These analyses are more or less in contradiction with the microscopic investigation. From the composition of the feldspars one would be justified in classing all the rocks as basalts, for in none is the anorthite percentage well below 50 %. On the other hand the SiO_2 content of all the types is higher not only than the average, but at the extreme limits of their respective groups. Thus the basic basalt is of average chemical composition (with exceptionally high Al_2O_3); the intermediate basalt belongs to the most acid, quartz-free basalts and would be classed as an andesite on the analysis only. The basaltic andesite is a very acid andesite chemically and corresponds to an average dacite with low Al_2O_3. The vitro-andesite is more acid still and from a chemical point of view an average rhyolite.

Concerning the distribution of the types of rock we find that the two basic basalts were found on the slopes of the northern cone. The intermediate basalts in the same parts and moreover in the caldera and on the main cone. The andesitic basalts were only encountered low down on the slopes of the caldera-cone. The basaltic andesites are limited to the central hills. The vitro andesites were found in the caldera and as loose fragments on the central hills.

GORGIADÈS BEY (bibl. 16) described a number of samples collected by Gogarten around Mamoeja on Halmahera. These rocks vary much less than those of Tidore, the extremes containing 46.56 % SiO_2 and 49.53 %. They all contain the same minerals: basic plagioclase, augite and olivine.

10. SKETCHES OF P. POERA BESAR, DAMAR, TERNATE AND MAITARA (fig. 33—38).

A few remarks on P. Poera Besar are to be found in Part 2,

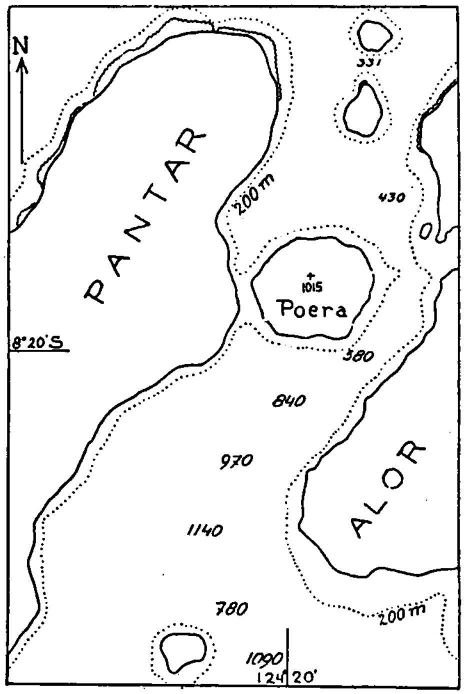

Fig. 33.

Map of the surroundings of P. Poera Besar, scale 1: 400.000.

Vol. V, of the Snellius-Expedition, p. 54. A geological description of

Fig. 34.

P. Poera Besar seen from the south.

Fig. 35.

P. Poera Besar seen from the northeast.

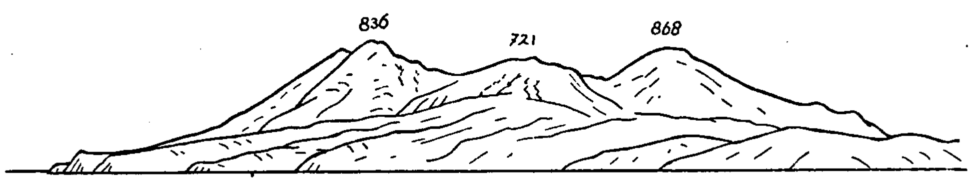

Fig. 36.

Eastern peninsular of Damar seen from the Wilhelmus baai in the northwest.

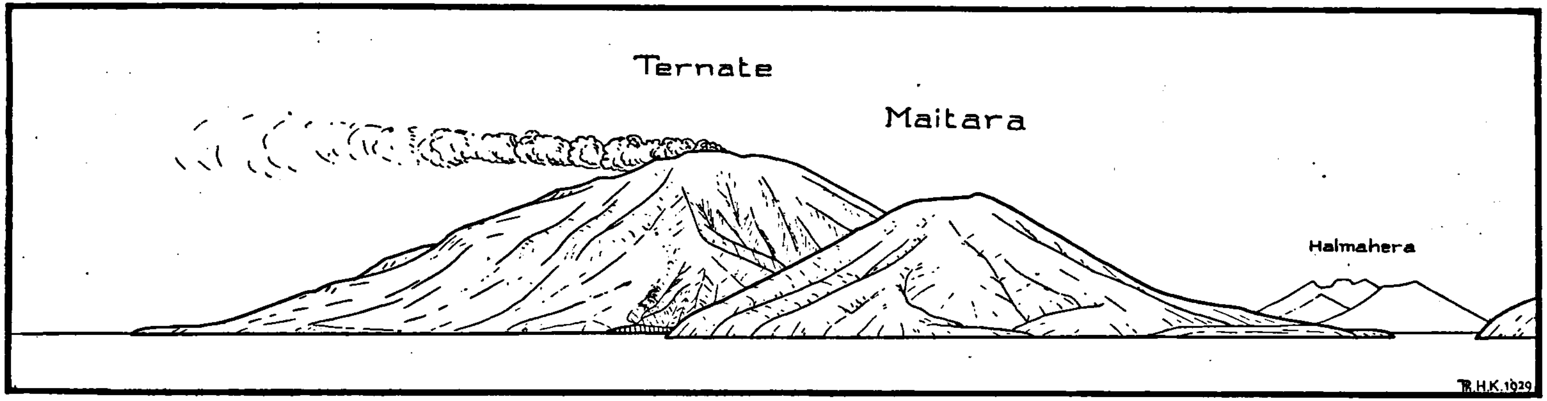

Fig. 37.

Ternate and Maitara seen from the south at Ome on Tidore.

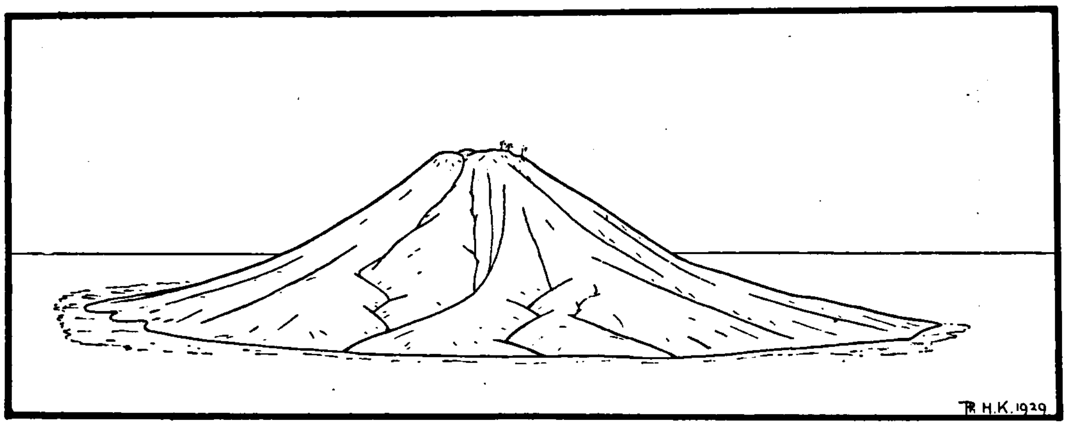

Fig. 38.

Maitara seen from the east on Tidore.

Damar is given by MOLENGRAAFF in bibl. 24. Several writers have dealt with Ternate: VERBEEK, WICHMANN, BROUWER, KEMMERLING.

11. REMARKS ON THE PETROLOGY OF EAST INDIAN VOLCANOES (fig. 39—46).

A. The chemical investigations by Esenwein.

We must first take careful note of the important investigations by ESENWEIN on the chemical aspects of the differentiation of the magma that fed recent East Indian volcanoes. He made a number of analyses of rocks from the volcanic island Paloeweh, north of Flores and of the Tanggamoes in southern Sumatra.

ESENWEIN found on examination of a number of lava's, basic cognate inclusions and hornblende crystals of Paloeweh (bibl. 14) that, although there is a fairly wide range of compositions, the variation diagram is comparatively simple. This is further illustrated by calculating the projection points of the various rocks in the silification triangle of NIGGLI (bibl. 26). As all minerals have a definite position in this projection along with the magma's, it is easy to deduce which minerals influenced an observed differentiation course in the triangle. When the course of variation is represented by a straight line a simple and unaltering substraction has called forth the differentiation, according to ESENWEIN. In the case of Paloeweh it is found that a straight line connects the projection points and that the substraction of the basic inclusions from the primary magma would cause the remaining liquid to assume the composition of the more acid rocks analysed (see fig. 39).

In a later publication (bibl. 15) the rocks of the Tanggamoes volcano are treated by ESENWEIN. Again he finds a straight line in NIGGLI's triangle. This line also passes through the projection points of the average plateau basalt, the Paloeweh basic inclusions and the Paloeweh hornblende. The course of the differentiation is slightly different, pointing more in the direction of the projection point of quartz. (By mistake the projection point of the Paloeweh hornblende was drawn in a wrong position in ESENWEIN's figure 8, p. 59, but not so as to influence the general reasoning).

There is, however, a drawback to the use of the triangle for illustrating problems of differentiation. As the projection point of the hornblende falls on the differentiation line, substration of this element alone from the plateau basalt would cause a differentiation along this line and apparently produce the plagioliparites of Tanggamoes. But if one calculates the composition of the magma's that result from this substraction, entirely different products are found to result, although their projection actually falls on the differentiation line.

It for instance we substract hornblende to the amount of half the weight of the basalt the resulting magma has the composition:

si = 212, al = 43, fm = 31.5, c = 17.5, alk = 8. The projection point is given by: Ls = 0.56, Fs = 0.06, Qs = 0.38. The projection point of the Tanggamoes latite is: Ls = 0.55, Fs = 0.06, Qs = 0.39, sothat the two rocks almost coincide. The composition of the latite is quite different, however, namely si = 359, al = 39, fm = 18.5, c = 12.5, alk = 30.

The reason for the great differences between various magma's falling on the same differentiation-line is the following: The ratio of fm: [c-(al-alk)] is of no consequence. The k- and mg-numbers do not influence the projection point. The feldspar may vary from alkalin feldspar to anorthite, with corresponding alterations of the other constituents for any given projection point.

From this it follows that although every magma has a definite projection point in the silification triangle, each point corresponds to a wide range of composition. The consequence is that a simple substraction differentiation will, it is true, be projected in a straight line, but that a number of points falling on a straight line does not prove, as ESENWEIN would have it, that they are members of the same simple substraction series (e.g. E in fig. 39 = Pb in fig. 41).

An obscure point in ESENWEIN's deductions can now be made clear. In bibl. 14, p. 137, he says:

„Scheidet sich nun durch irgend einen Kristallisationsprozess aus „dem so angenommenen Urmagma Hornblende von der Zusammen- „setzung A oder B (gleichzeitig oder später von basischem Plagioklas „gefolgt) aus, so muss die Restschmelze ihren Chemismus in der Pfeil- „richtung nach oben verändern. Entziehen wir, mit andern Worten, „dem nicht differentiierten Magma Gesteine oder Magmenteile von der „Zusammensetzung der basischen Einschlüsse, so muss der Rückstand „notgedrungener Weise seinen Chemismus in Richtung dessen der jungen „Paloewehlaven hin verändern.''

It is not clear what the feldspar has to do with this reasoning as the hornblende alone would also cause the differentiation, if ESENWEIN's use of the triangle were correct. On the contrary a combination of these two (B in fig. 39) would cause a differentiation in the direction from E (= plateau basalt) to E—B. The reason that feldspar was added by ESENWEIN is doubtless that it forms part of the basic inclusions. I already showed that the hornblende alone cannot explain the differentiation and why its falling on the differentiation line is in no way proof either. As far as can be seen from the silification triangle the basic inclusions, however, might have caused the differentiation, but for the same reasons as were given for the hornblende this is not necessarily the case.

At first sight it seems curious that these basic inclusions are also projected on the differentiation line. The following may account for it.

According to ESENWEIN's description the inclusions contain, besides a large amount of hornblende (A in fig. 39), a considerable quantity of basic plagioclase. A combination of these two minerals in about equal amounts must present a projection at B. A small additional amount of pyroxene brings the projection to C and a final addition of magnetite carries the combination to the projection point of the basic inclusions D. This fits in exactly with the microscopic examination.

It is obvious that the substraction of these inclusions from plateau basalt must result in an entirely different product than from the crystallisation of hornblende alone, although the same line is followed in the triangle. That the hornblende is also projected on the same differentiation line is merely a coincidence. In how far the basic inclusions can be considered as the cause of the differentiation will be followed out in detail presently in the variation diagram, where it will be shown that the inclusions represent a magma enriched by crystal sorting, but not of the same composition as the materials that were substracted to cause the differentiation (p. 322).

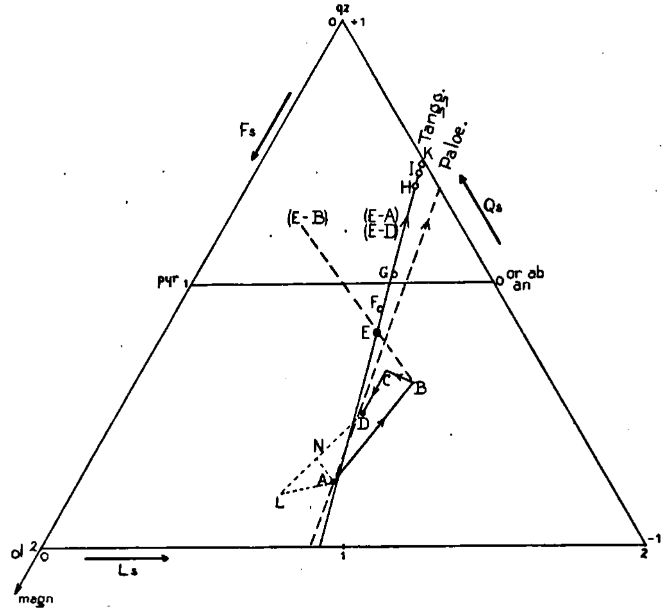

Fig. 39.

Silification triangle illustrating various aspects of the differentiation series of Paloeweh and the Tanggamoes.

The great value of the silification triangle for illustrating the differentiation is in no way denied by the writer. However, it should only be employed in combination with a variation diagram as one may otherwise be led to entirely wrong conclusions, as shown above. In many cases, where detailed treatments are to be made, even the NIGGLI-variation diagram can only be used to gain a first impression, as all major components must be taken into account. This can either be done by drawing separate K, Na, Fe, and Mg curves in the NIGGLI diagram or by using a weight percentage diagram of HARKER's type.

By way of example we can again consider ESENWEIN's triangle (fig. 39). D represents the composition of the basic inclusions (hornblende, plagioclase, magnetite and pyroxene). But besides the inclusions the same point might also represent:

hornblende + olivine (L) and plagioclase (or orthoclase);
hornblende + pyroxene (N) and felspar;
hornblende, feldspar and silica; etc.

A choise between all these possibilities can only be made by studying a complete differentiation diagram.

The various curves in the NIGGLI diagrams given by ESENWEIN are practically straight. This in itself already points to a simple substraction differentiation and the triangle need not be used to prove it.

In another, minor detail ESENWEIN's deductions need correction. The latite of Tanggamoes consists of a plagio-liparite with inclusions of basalt. ESENWEIN uses NIGGLI's values to calculate the relative amounts of the two components necessary to produce the latite. He arrives at the conclusion that 29 % of basalt is incorporated in 71 % of plagio-liparite. NIGGLI's values, however, cannot be used for calculating relative amounts as they are not proportionate to these. The average amount of SiO_2 of the basalts is 52.28 % and of the plagio-liparites it is 73.41 %. The percentage of SiO_2 of a rock composed of 29 % basalt and 71 % plagio-liparite would be 67.28 %, whereas the percentage of the latite is actually 70.63 %. By mixing 12.2 % of the acid basalt with 87.8 % basic plagio-liparite a magma is produced of the following composition:

	mixture	latite
SiO_2	70.63	70.63
Al_2O_3	13.49	12.93
CaO	2.06	2.34
Alkali	7.17	7.39
MgO	0.79	0.87
Fe_2O_3	1.29	1.24
FeO	1.22	1.59

ESENWEIN's conclusion that a mixture of the two magma's will produce the latite is correct, but the amount of basalt needed is much smaller, only 12 % instead of 29 %. As the visible amount of basalt inclusions in the slide is 15—20 % one must conclude that no melting of the basic inclusions took place. The reaction according to BOWEN's principle, however, has altered the composition of the plagio-liparite magma so as to prohibite the crystallisation of quartz and biotite in the latite. This conclusion is more probable than ESENWEIN's deduction that 9—14 % of the rock was composed of fused basalt. This would have been in contradiction with the reaction principle, but need no longer be assumed in the light of the corrected calculation.

Apart from these minor points ESENWEIN's studies on the differentiation are of the greatest importance and should be carefully studied by all interested in these problems.

B. Inclusions in the lava's and the formation of the hornblende.

Many lava's of recent East Indian volcanoes are very rich in inclusions. BROUWER was the first to realise their importance and to him we owe the description of a great number of inclusions from several volcanoes (bibl. 7—10). Apart from a few exceptions they are to be considered according to BROUWER as parts of the same magma as the enclosing lava's, crystallised at greater depths. One of the most interesting properties of the inclusions is the frequent occurrence of hornblende crystals, sometimes decomposed to pyroxene and ore. BROUWER was able to show that where the inclusions cooled rapidly in bombs the hornblende is idiomorphic and unaltered, but that when they are taken from lava's, especially from lava plugs, and thus cooled more slowly, the hornblende is generally considerably or entirely changed to pyroxene and ore. From this he draws the important conclusion, that the hornblende formed at greater depths, but was no longer stable when arriving at the surface. Only in the case of rapid cooling did they forego alteration. (Independently KEMMERLING later came to the same conclusion, bibl. 18). The glassy groundmass of some inclusions proves that they had not yet entirely crystallised at the time of eruption.

BROUWER is of opinion that these inclusions represènt the cooled border of the magma at depths, brought up by renewed activity. He does not believe that any appreciable differentiation took place, because the repeated eruptions of each volcano reproduce practically the same lava. There were no analyses of inclusions available for verification at that time.

Afterwards BROUWER found a lava (bibl. 11) containing unaltered hornblende as normal phenocrysts in the submarine lava plug of the Mahengetang volcano north of Celebes. To account for this case he assumed that the rapid cooling of the lava below water, the advent of volatile substances and the higher pressure of the water prohibited the alteration of the hornblende in the normal fashion.

BROUWER's general conclusion is that considerable pressure and a high content of volatile substances favour the crystallisation of hornblende, but that at still higher pressure (that is lower down in the magma chamber) the augite phenocrysts are formed in the magma. When the latter forces its way to the surface, carrying along the partly consolidated roof with hornblende crystals, the reduced pressure and the escape of the volatile substances brings the magma outside the stability field of the hornblende. The latter is then resorbed.

KEMMERLING critisised BROUWER's theory (bibl. 19). He pointed to the fact that the dome of Mahengetang rose above low water and was therefore not exposed to abnormal pressure. To this we might add that in thick lava flows and plugs the lower parts consolidate under considerable pressure without containing hornblende crystals in most cases. KEMMERLING also questions the influence of cooling below water, because lava's that consolidated below crater lakes (Galoenggoeng) do not show hornblende phenocrysts. The low conductability of lava must also annihilate the influence of cooling water a short distance below the surface.

These arguments find further confirmation in the discovery of lava plugs (tholoïden) on the Penanggoengan (see page 282) with hornblende as normal, unaltered phenocrysts even at the very surface. Neither the influence of water nor of pressure can be held responsible for the preservation of these hornblende crystals.

We must therefore seek another explanation for the exceptional cases in which the hornblende is not decomposed in a lava that cooled slowly at the surface. It is of importance to note that in several domes the conditions appear to have been favourable for the preservation of the hornblende (Penanggoengan, Mahengetang, Kloet). The lava of these plugs must have cooled comparatively slowly. We are therefore forced to assume that in these cases the hornblende remained stable during the entire process of consolidation. That, however, the stability field of the hornblende was nearly left, is proved by the cases in which decomposition has just started at the end of the consolidation. As BROUWER and KEMMERLING showed convincingly that the materials of most inclusions passed right out of the stability field of the hornblende there must be a difference in composition.

According to BROUWER the presence of volatile substances is favourable to the formation of hornblende. We might suppose that the plugs contained a relatively high percentage. But this would also increase the fluidity whereas plugs are formed in consequence of the viscosity of the lava and no explosive phenomena appear to have accompanied the eruption. The opposite assumption, that loss of volatile substances caused the extention of the stability field of the hornblende is rendered improbable by the occurrence of domes without hornblende (Merapi, Galoenggoeng) and the frequence of hornblende in inclusions.

There seems to remain but one possibility, namely that the chemical composition of the non-volatile part of the lava, that consolidated to hornblende andesite plugs, was different to the normal magma of the pyroxene andesites and basalts.

These differences must be very slight, however, as the analysed plug-rock of the Penanggoengan has a normal composition. Evidently some very slight alteration of the composition extends the stability field of the hornblende to lower temperatures. The frequent occurrence of hornblende in the lava's of Tidore without any apparent abnormality in the composition points in the same direction.

The chemical analyses by ESENWEIN of the inclusions of Paloeweh enabled him to prove that they are basic differentiation poles (see, however, our remarks on this subject, p. 322). In a different manner this also holds for the basic inclusion of Tidore, that consists of normal magma with the addition of a large amount of hornblende (see p. 326). BROUWER's conjecture that the inclusions are only a heteromorphic facies of the same magma as the lava's is therefore not born out. The analysed examples did not arise by the breaking up of the consolidated roof portions of the magma in the chamber, but from crystal sorting in the deeper layers. There is also no reason to assume that below the parts where the hornblende is formed, there is a region where the pressure again carries the magma beyond the stability field of this mineral. The hornblende-free lava's can be explained by crystal substraction, leaving a composition outside the stability field of the hornblende, even at higher temperatures.

With a view to the importance of the inclusions for the differentiation an attempt can be made to determine the most probable quantitative, mineralogical composition. The graphic method is the most easily followed.

The average composition of two unchanged Paloeweh inclusions and of the Kloet inclusion and the average of three hornblende analyses (2 from Paloeweh and 1 from the Kloet) are the following:

	hornblende	inclusion	calculated inclusion
SiO_2	40.11	41.29	41.1
Al_2O_3	12.14	18.60	20.1
FeO	13.17	11.46	12.2
MnO	0.17	0.19	0.1
MgO	12.88	7.13	7.4
CaO	13.19	14.37	14.2
Na_2O	3.82	2.70	2.8
K_2O	1.13	1.11	0.6
+ H_2O	0.45	0.68	0.2
— H_2O	0.07	0.26	0.1
TiO_2	1.91	1.19	1.0
P_2O_5	—	0.16	—

The plagioclase contains on an average 87½ % An. There is further a considerable amount of magnetite, some hypersthene pour in iron and some light green augite. For the hypersthene the composition given in the following table may be supposed. That of the augite is more or less arbitrarily chosen, but although it may be different the influence of the mistake is not great on account of the small amount.

	hypersthene	augite
MgO	22.4	17.1
CaO	1.9	21.7
FeO	20.2	4.2
Al_2O_3	1.1	2.3
Na_2O	—	1.5
K_2O	—	1.0
SiO_2	52.2	52.5

When hornblende (Ho, fig. 40) is substracted from the inclusions (In) the thin full lines (In-Ho) are followed. The composition of the remainder must lie to the right of In and to the left of 43 % SiO_2 where the amount of MgO becomes zero. The composition of the plagioclases is given by the double lines (Pl) from anorthite (An) past An 75 %—Ab 25 %. If we combine one part hypersthene and one part augite (together Px) with 2 parts magnetite the composition MaPx is reached, just over 26 % SiO_2.

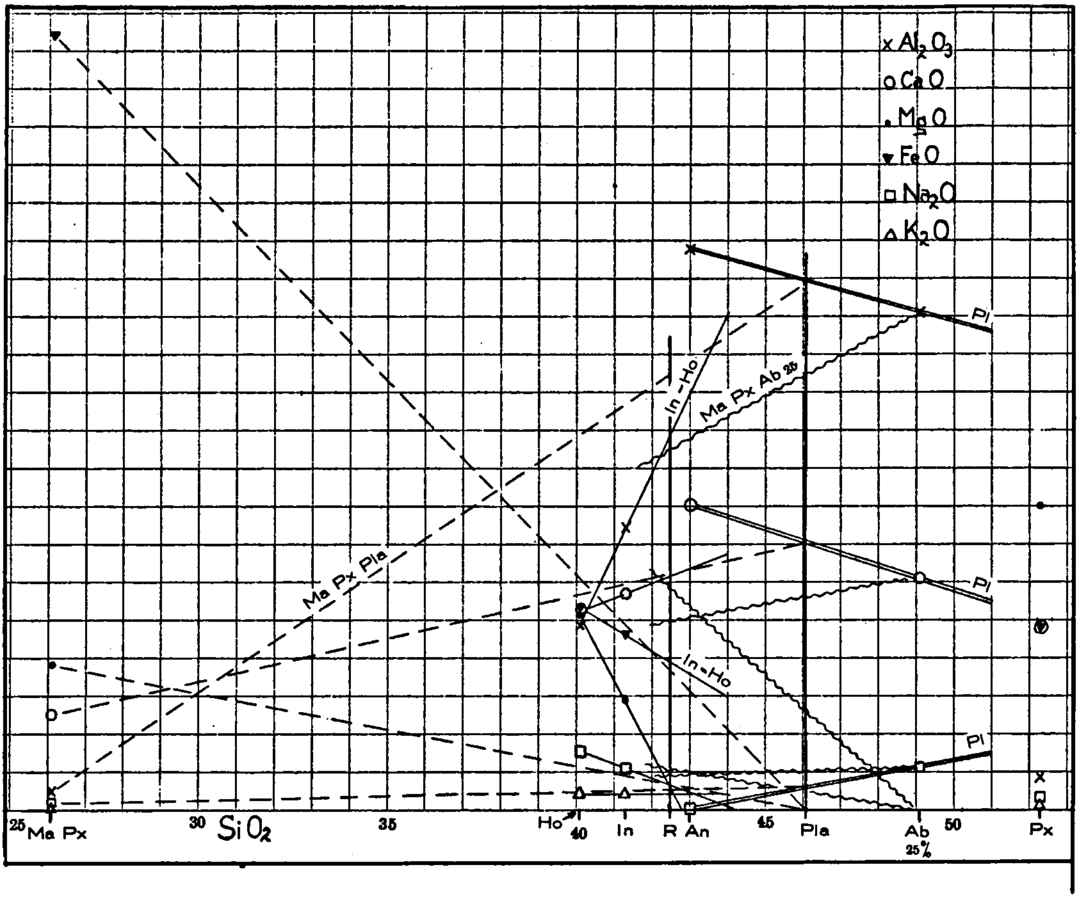

Fig. 40.
Variation diagram for finding the composition of the inclusions of Paloeweh.

The dotted lines show the composition of mixtures of plagioclase of 87½ % An (Pla) and MaPx. If the average compositions and supposed amounts were correct then the two sets of lines (MaPxPla and In-Ho) should bisect on a vertical line giving the composition of the inclusions, minus hornblende (R).

Although this is not found to be the case the differences are relatively small. For FeO, CaO, MgO, Na_2O and K_2O the differences are less than one percent; only for Al_2O_3 do they amount to 3½ % [1]).

[1]) These divergencies are lessened by half when the whole inclusion is considered (1 R + 1 Ho).

The weight percentages of the various components in the inclusions is found to be: hornblende 50 %, plagioclase 40 %, magnetite 5 %, hypersthene 2½ %, augite 2½ %. This combination is calculated in the last column of the table on page 320.

Although there are several uncertainties in the conclusion arrived at it will be found that comparatively slight alterations either in the relative amounts of the constituents or the addition of other minerals carry us further away from the attempted correlation. Thus with a composition of the plagioclase of 25 % Ab (that is less than the average of the Fedorof measurements and for this reason alone already improbable) the bisection of In-Ho with the waved lines MaPxAb25, fig. 40 would give the inclusions minus hornblende. It is found that Al_2O_3, MgO, Na_2O and K_2O are correct within one percent, but CaO is 2½ % too low, FeO 5 % too high. If magnetite is left out of account FeO of the inclusions is not only made several percent too low, but the SiO_2 content is at least 4 % too high. Without pyroxene the difference for Al_2O_3 is increased some 3 % and FeO falls out 2½ % too low for the inclusion minus hornblende.

These considerations bring out clearly the importance of all the constituents for gaining the correct composition of the inclusions and therefore carry us back to the conclusion that the NIGGLI triangle, as used by ESENWEIN for illustrating the course of the differentiation, can only give us a very incomplete insight into the processes at work. It will also be seen that for details the NIGGLI variation-diagram would have to be used with separate lines for Mg, Na_2O and K_2O.

An interesting problem is to ascertain whether the differentiation of the Paloeweh magma can be explained by substraction of the inclusions from the most basic lava's as ESENWEIN believes (see quotation on p. 315.

An examination of fig. 41 shows that a simple substraction differentiation is possible as the lines of the various constituents are straight. The lack of analyses of intermediate lava's renders this conclusion somewhat doubtfull, but it is certainly the most probable assumption that can be based on the data at hand. In the same figure the average of both recrystallised inclusions is included (about 47 % SiO_2) and is found to coincide accurately with the continuation of the differentiation lines on the basic side. As this may be in part attributed to BOWEN's reaction principle on account of the recrystallisation of these inclusions one cannot attribute the same importance to them as to the other inclusions.

The average of three unaltered inclusions (two from Paloeweh, one from the Kloet) shown in the same figure (at about 41 % SiO_2) is seen to deviate considerably from the differentiation lines and the same holds for each separate inclusion.

In other words the differentiation of the Paloeweh rocks cannot be directly attributed to the substraction of the basic inclusions! The principal differences are that the Al_2O_3 and K_2O are too high in the inclusions, while the FeO and Na_2O are too low, CaO, MgO and TiO_2

are practically what were needed to produce the observed differentiation.

In itself this conclusion is not surprising. In order to change the composition of a magma the crystals must be carried away from the

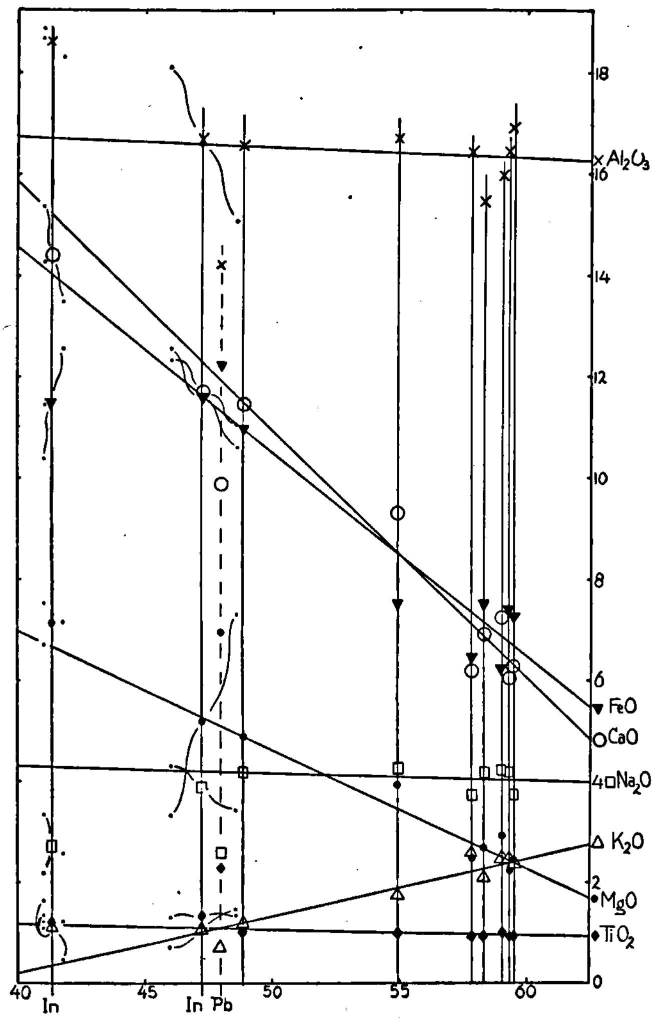

Fig. 41.

Variation diagram of Paloeweh. Pb = plateau basalt.

remaining liquid (by gravity), for if they remained the bulk composition would not be altered. It seems most improbable that these crystals would collect again unchanged elsewhere in the correct ratio's (as crystals or resorbed into the magma) and then be erupted in the form of inclusions. It is more rational to assume that the inclusions represent a nearly or entirely crystallised magma that was formed by the showering of crystals from a higher level (in the act of crystallisation) into lower strata. Some of these phenocrysts were caught (by resorption or continuation of growth) and others passed through being partly resorbed and again others escaped to deeper magma without loss.

These considerations bring out the importance of the difference between the materials that were substracted and the various products that may be formed by the addition of sunk materials to the original magma. Our quotation from ESENWEIN (p. 315) shows that he has not sufficiently stressed this point. BOWEN on the other hand draws special attention to it.

When viewed in this light the basic inclusions give us valuable indications of the kind of crystals forming at depths and thus causing the differentiation, but they need not have a composition fitting into the differentiation series. This would only be the case if they had been formed as floating balls by „Sammelkristallisation".

For the composition of the materials that did actually cause the differentiation by sinking away from the upper layers of the magma chamber, any series of points on a vertical line where it is cut by the various oxide lines in fig. 41 could be assumed at the basic side. We can however, attempt to find such a combination of the minerals found in the inclusions as to give one of these possibilities. The task would be almost hopeless if we did not use the results of the analysis given before of the probable quantitative mineralogical composition of the inclusions.

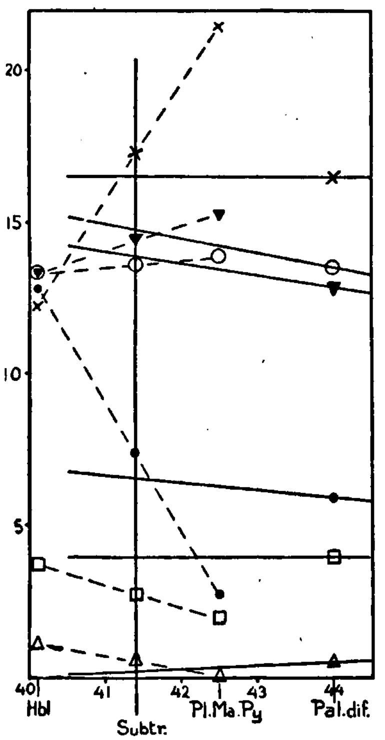

Fig. 42.

Variation diagram for finding the composition of substracted material in the Paloeweh differentiation.

We see from fig. 40 that in order to increase the relative amount of FeO as compared with the inclusions a more acid plagioclase must be taken in smaller amounts for instance 25 % Ab (the waved lines) whereby we attain at the same time the necessary increase of Na_2O and decrease of Al_2O_3 (the TiO_2 is contained in the magnetite as titanomagnetite actually observed by ESENWEIN). The only components that do not fit in correctly are CaO and MgO. This can be corrected by reversing the proportion of these two oxides in the pyroxene.

In fig. 42 Pl.Ma.Py is the combination of 64 % plagioclase (25 % Ab), 14 % magnetite and 22 % pyroxene of the same composition as that of fig. 40 but with the amounts of CaO and MgO reversed. The dashed lines are the combination of the average hornblende with this mixture. Subtr. represents the composition of the combination of 46 % hornblende, 34 % plagioclase (25 % Ab), 8 % magnetite, 12 % pyroxene. The composition of Subtr. nearly fits onto the drawn out lines that represent the differentiation lines of the Paloeweh magma on the basic side. Al_2O_3, FeO, MgO and K_2O are about one percent too high; CaO and Na_2O one percent too low. The given combination of minerals therefore gives us a fairly correct notion of the matter that sank away thus causing the Paloeweh differentiation.

In order to cause the differentiation to more acid magma the plagioclase should be more basic than the average of all the plagioclase material in the initial magma. As the normative composition of the plagioclase of the most basic lava is about 50 % Ab (ESENWEIN, p. 128) this requisition is met by the composition assumed (25 % Ab). On sinking into deeper strata it will be resorbed and render the resultant liquid more basic. The first plagioclase to crystallise from this new melt would be more basic than the resorbed crystals and might be represented in the basic inclusions (10 %—15 % Ab). If our deductions are correct the inclusions therefore represent the first crystallisation products of the basic pole of the deeper magma, or they may also have been formed from a magma that was produced by a second crystallisation differentiation. Complete crystallisation of the first enriched magma would have produced plagioclase with more than 25 % Ab, whereas the normative composition in the basic inclusions is about 10 % Ab. Repeated differentiation to produce the inclusions seems therefore to be more probable if they are parts of an entirely crystallised magma.

One characteristic of our assumed differentiation may still be pointed out. How is it that an increase of FeO as compared to the inclusions is attained chiefly by changing the composition of the plagioclase that does not contain iron?

Increase of the amount of FeO relative to pyroxene in fig. 40 would lower the amount of iron in the sinking material for a given percentage of SiO_2. This at first sight appears to be contradictory. To render this matter clear let us consider a magma composed of FeO, MgO, Al_2O_3 and SiO_2, which it is assumed has crystallised to magnetite (FeO), a mineral with m-MgO . n-SiO_2 and another p-Al_2O_3 . q-SiO_2 (fig. 43). Let us change the relative amounts of these components while leaving the SiO_2 percentage of the melt unaltered. The FeO- and MgO-minerals combine to some composition given by the drawn out lines and this composition combines with the Al_3O_3-mineral along the dotted lines.

In case B, fig. 43 where the Al_3O_3-mineral is more acid than the MgO-mineral, any increase of the amount of FeO as compared to MgO (moving A to the left) increases the amount of FeO for the given SiO_2-percentage (C).

In case A where the Al_2O_3-mineral contains less SiO_2 than the MgO-mineral, two cases arise. When the given composition of the magma is less basic than the Al_2O_3-mineral (D), relative increase of FeO as compared to MgO (moving B to the left) increases the percentage of iron in the magma. When, however, the given magma is more basic than the Al_2O_3-mineral (C), increase of iron relative to MgO (moving A

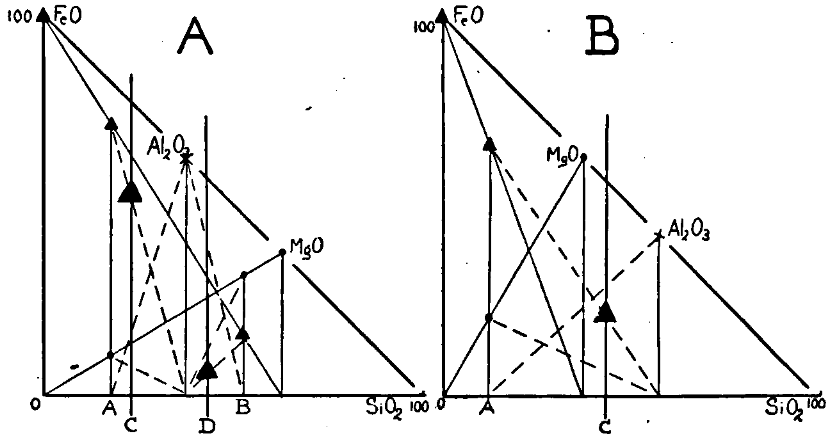

Fig. 43.

Variation diagrams to show the influence of the combination of various amounts of minerals on the combined composition.

to the left) decreases the iron-percentage in the magma! This is the case dealt with in fig. 40 where the Al_2O_3-mineral is represented by basic plagioclase and the MgO-mineral by the combination of two pyroxenes.

The inclusion of Tidore (see fig. 44) deviates a long way from the normal composition by the high MgO and low Al_2O_3 percentage and

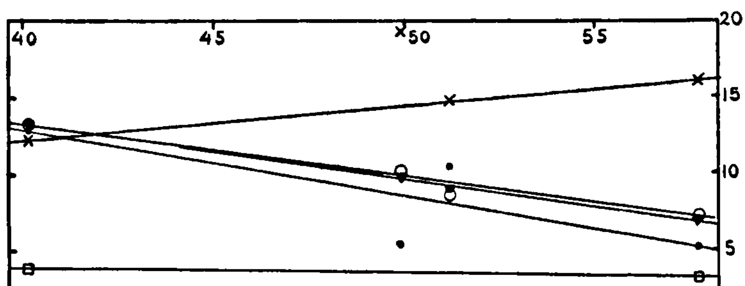

Fig. 44.

Variation diagram concerning the basic inclusion of Tidore.

should evidently be left out of account when considering the tendency of the differentiation. On the other hand it is of importance to ascertain whether these differences can be explained by the presence of hornblende that occurs abundantly in the analysed specimen. In fig. 44 is shown how the addition of 38 % average hornblende to 62 % of the surrounding rock (nr. 191) gives a composition that approximates to that of the inclusion. This combination would contain 2½ % too little MgO, 1 % too much CaO and 1½ % too much Na_2O. All other constituents are correct within 1 % (see the calculated composition in the table on page 309). If one takes into account that the composition of the hornblende may be somewhat different to what we have assumed, this result is sufficiently accurate to prove that the inclusion was formed simply by the addition of 38 % hornblende crystals to 62 % of the surrounding magma. As measurement showed the hornblende phenocrysts alone to form 31 % of the rock, the mode appears in close coincidence with the calculated norm.

This conclusion is of importance when compared to the probable mode of formation of the Paloeweh inclusions. The latter appear to have been formed by crystallisation of a magma enriched by the sinking of several kinds of crystals and thus represent a deeply formed basic pole of the differentiation series. The recrystallised inclusions have been changed afterwards by the reaction with the surrounding magma. The Tidore inclusion is probably more of local origin. The hornblende crystals are small and were evidently not resorbed. This conjecture is rendered more certain by taking into account than the other inclusions of the same island have different phenocrysts that vary in conjunction with the composition of the surrounding lava. Both the Paloeweh and Tidore types of inclusion, however, have in common that they differ in composition from the normal magma and were therefore formed by other processes than BROUWER assumed.

C. Variation diagrams of Tidore, the Penanggoengan and Krakatoa.

Tidore.

The number of analyses (188, incl., 191, 218, 201) is not sufficient to show accurately the mode of differentiation. Thus it is a matter of doubt wether the lines in the diagram fig. 45 are in reality curved or straight. In any case the amount of curvature appears to be small.

If we compare the differentiation series with that of Paloeweh we note a stronger decrease of Al_2O_3 and TiO_2 in the Tidore diagram, while FeO, CaO and K_2O lie slightly more horizontal. Na_2O on the other hand increases much more.

The Penanggoengan.

As there are only three analyses (96, 90, 99) to base the variation diagram on, two of which are nearly the same, not much can be said on this theme. On the whole it appears that the type of differentiation comes closer to that of Tidore than of Paloeweh. If the Tidore and Penanggoengan analyses are combined the lines are straighter than those for Tidore alone.

Krakatoa.

The Krakatoa variation diagram here given is based on a number

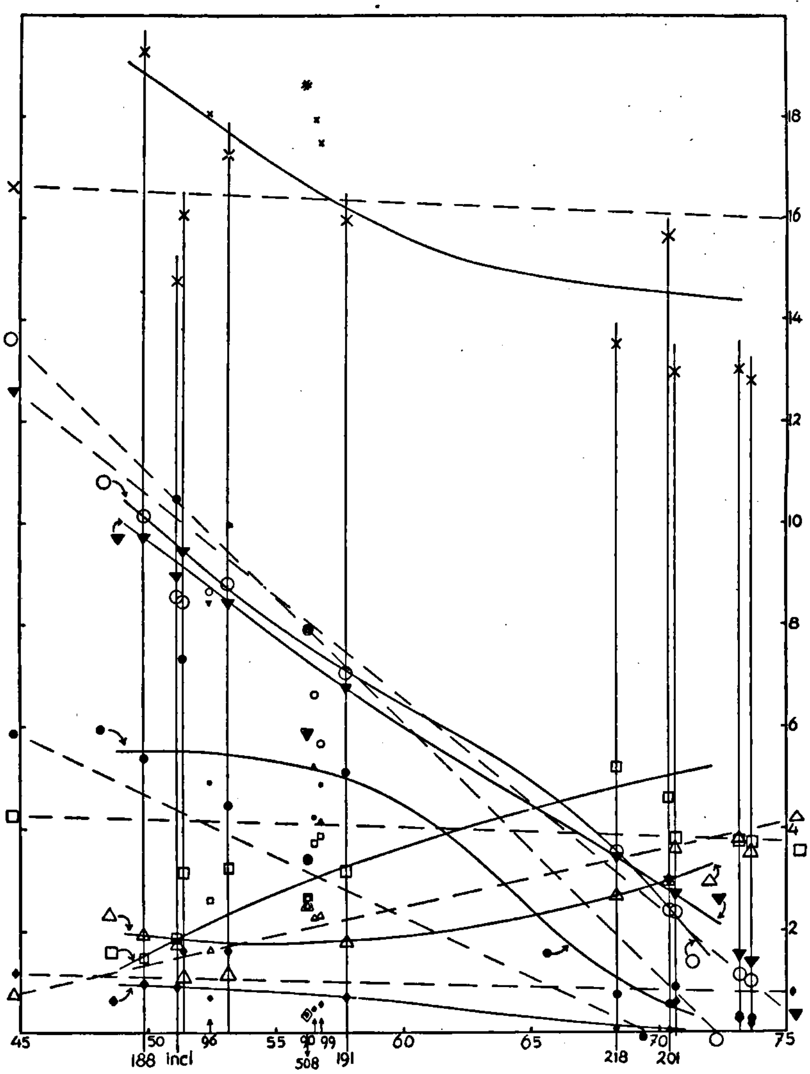

Fig. 45.

Variation diagram of Tidore, Penanggoengan, 508 = G. Api, Dotted lines are those of Paloeweh.

of analyses published by Stehn (bibl. 28). It is of a different type to that of Paloeweh as the differentiation lines are markedly curved.

It is not a simple substraction differentiation therefore, but has the normal aspect with bent lines indicating that in the course of the

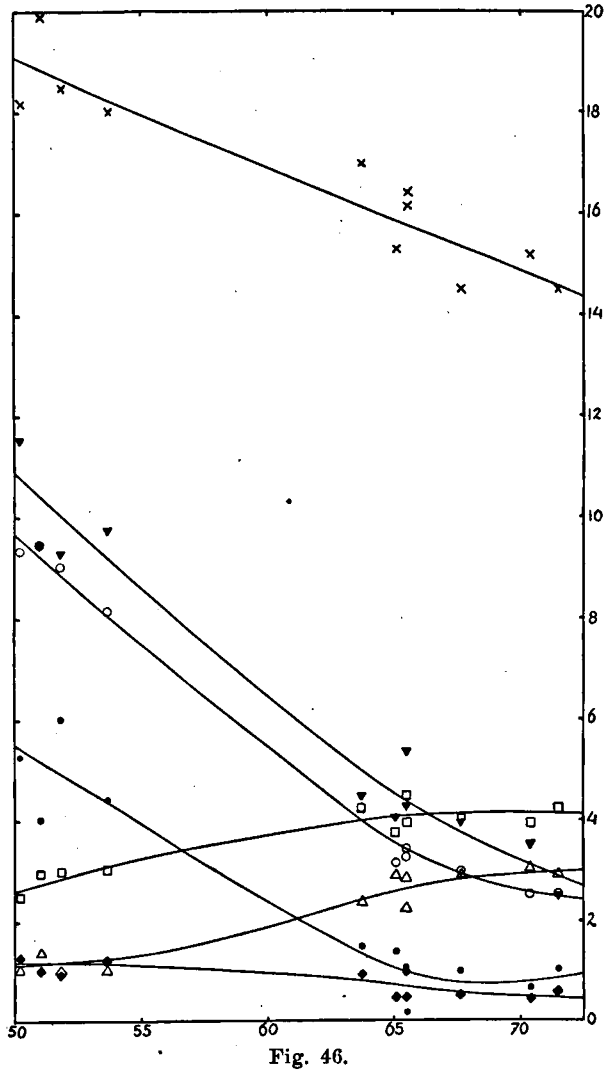

Fig. 46.

Variation diagram of Krakatoa.

differentiation the composition of the sinking crystals continually changed. I have added this diagram to show that there are evidently many types of differentiation in the recent East Indian volcanoes.

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