EXPERIMENTS ON THE FORMATION OF VOLCANIC CONES

(In connection with East Indian volcanic islands)

BY

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I. INTRODUCTION.

Several investigators have tackled the problem of the main causes that produce the slopes of volcanic cones, especially with a view to explaining the characteristic concave profiles of strato-volcanoes *). A satisfactory result has not been arrived at, however. This became evident to the present author while studying the submarine slopes of volcanoes in the East Indies. A number of submarine sections of isolated volcanic piles were constructed from the echo-soundings of the Snellius Expedition and from the data contained in the fair sheets of the Hydrographical Survey. These sections combined with the corresponding subaerial profiles will be reproduced in the Scientific Results of "the Snellius Expedition, Volume V: Geology, Part 1: Geological Interpretation of the Bathymetrical Results", together with a discussion of their shapes and the mode of their formation. An explanation of the wet part of the slope is not possible, however, until we understand the agents influencing the dry part. But as we said, this subject has not been adequately treated. An attempt had therefore first to be made to analyse the factors that play a part in the production of subaerial slopes of volcanoes. In order to test the validity of the deductions an experimental investigation was undertaken that will be described below. These experiments were carried out in the laboratory for experimental geology in the Leyden geological institute.

*) In the English language the term "strato-volcano" is not in general use, as in German, to denote a volcanic cone built up of successive layers of ash, lapilli, bombs and lava flows. It is used here on account of the ambiguity of the alternative term "normal cone".

II. THE CHARACTERISTIC CONCAVE SLOPE OF VOLCANOES.

Most strato-volcanoes, especially the larger cones, show a markedly concave slope. Directly outside the crater, or only slightly beyond, the flanks of the volcano fall abruptly away on all sides in steep slopes of 20°—40°. Gradually the declivity decreases, sweeping out towards the foot in a broad flat plain, that gradually merges into the surface of the foundation on which the volcano was erected.

Various authors were struck by this characteristic and sought to explain it by several causes. POULET SCROPE (according to MILNE) thought that the production of lava from lateral vents and the washing down of loose products by rain are the principal agents. MILNE [1]) and BECKER [2–4]) both believed that the self supporting mass of loose materials tends to assume a logarithmic or other mathematic curve as giving the greatest stability to the pile (although the former also pointed to the influence of erosion and of variations in the nature of the loose particles). VON WOLFF [5]), p. 233—236, pointed out that this can hardly be the cause, as other structures of similar shape do not spread out by their own weight. JUDD and WOODWARD [6]) made experiments to ascertain the shape of cones formed by the piling up of ejectamenta around a vent. They concluded that the slope is straight. Later LINCK [7]), without knowing of this experiment, made a similar experimental investigation, that led him to doubt, even, that concavity of the slope is the general rule. We will not sum up all the authors that have used the same agents to explain the concavity, as they have not added new arguments to the discussion. The opinion most generally given is that the concave slope is to be explained by erosion.

There is, however, yet another method by which a concave slope could be produced, that has been overlooked so far. If there were considerable variation in the force of the eruptions of a volcano, the resulting slope could attain all manner of sections.

III. THE INADEQUACY OF LINCK'S EXPERIMENTS.

First we must consider why the experiments of LINCK led him to a wrong conclusion concerning the shape of volcanic cones.

LINCK's experiments may be shortly described as follows. From a cylinder of compressed oxygen a tube was led to a hole in a horizontal table. Into this tube could be introduced sand of various colours that was carried along by the current and thrown up out of the hole in the table. A stratified miniature cone could thus be built up round this crater on the table. A pane of glass at each side of the hole divided the model in two, without influencing its shape. On removal

[1]) See bibliography.

of one half, the successive layers could be studied and photographed through the glass.

It was found that the sand falls thickest some distance away from the hole in the table. The model grows into a circular mound with a steep slope down to the edge of the hole, a convex apex and a fairly straight and less steep slope outwards with a small concave curve by which it merges into the horizon of the uncovered table. The building up was carried on until sand began to slide back in the crater into the hole of the table.

Practically the same result was obtained in all the experiments, although slight variations occurred, especially when for some reason that LINCK does not state, the building up of the tube opening a few mm enabled a new layer to be added on the inside of the crater.

The question arises why this elegant experiment that appears to imitate so closely volcanic activity of strato cones, results in a convex slope, although it is evident to all who have seen large strato-volcanoes or good photographs and contoured maps of these, that the slope is straight or decidedly concave. The answer is not far to seek. The experiment only illustrates the first phase in the construction of a volcanic pile. The crater bottom in nature does not remain at the level of the top of the neck in the substratum, but it grows upwards gradually in the interior of the volcanic cone. Agglomeration of the loose materials and plugging by lava harden the interior of the volcano. Each successive eruption will therefore take place from a slightly higher level inside the mountain, until the neck has been elongated to hundreds or even thousands of meters above its original orifice.

There are other influences on cone construction, that the experiments do not take into account such as: 1. variations in the size of the particles, 2. variations in the force of eruption, 3. the intercallation of lava flows between the layers of loose particles, 4. the influence of erosion, 5. variations in the relative amount of gas and 6. the collapse of a certain amount of the top of a volcano after the eruption. Several of these influences were already mentioned by LINCK. Where the slopes of volcanoes do not conform to his experimental results (and this is more often than he believed), these agents are thought to have played a part. It will be seen further on, that in the experiments the force of the eruptions is also much greater as compared to the size of the model cone (if it is to represent a full-grown volcano) than in nature. This also proves that the experiments were stopped long before a true imitation of a volcano had been attained.

It was with a view to studying the effect of these agents that the experiments, here to be described, were carried out.

IV. DESCRIPTION OF APPARATUS.

The apparatus used was the following. The current of gas (air) was procured from two vacuum cleaners (blowing) coupled in series so as to obtain a stronger current than is possible with only one. In one experiment a bicycle footpump was employed for short, sharp eruptions (A fig. 1). A rubber tube with a screw clamp (B) for regulating the strength of the current, was fixed onto a T-shaped glass tube (E) through which the sand was introduced from a large funnel (D) with a stopper. The latter is needed to prevent the air escaping by way of the funnel. A second screw clamp was used for regulating the supply of sand (C). The sand was shaken up with red or white powder to mark the stratification. The mixture of sand and air was led by a rubber tube into the wooden blow pipe (F) with an aperture of 10 mm. The latter passed through the table (H) in a layer of felt (G), sothat it could be pushed up and down without sand leaking through out of the model on the table. In order to prevent also the leakage of sand from behind the panes of glass (I and J) when one half of the model had been removed to study the internal stratification, grooves were made in the blow pipe into which the panes were let for a couple of mm (K). The figure 1 of Plate 1 (p. 109) will make these details clear.

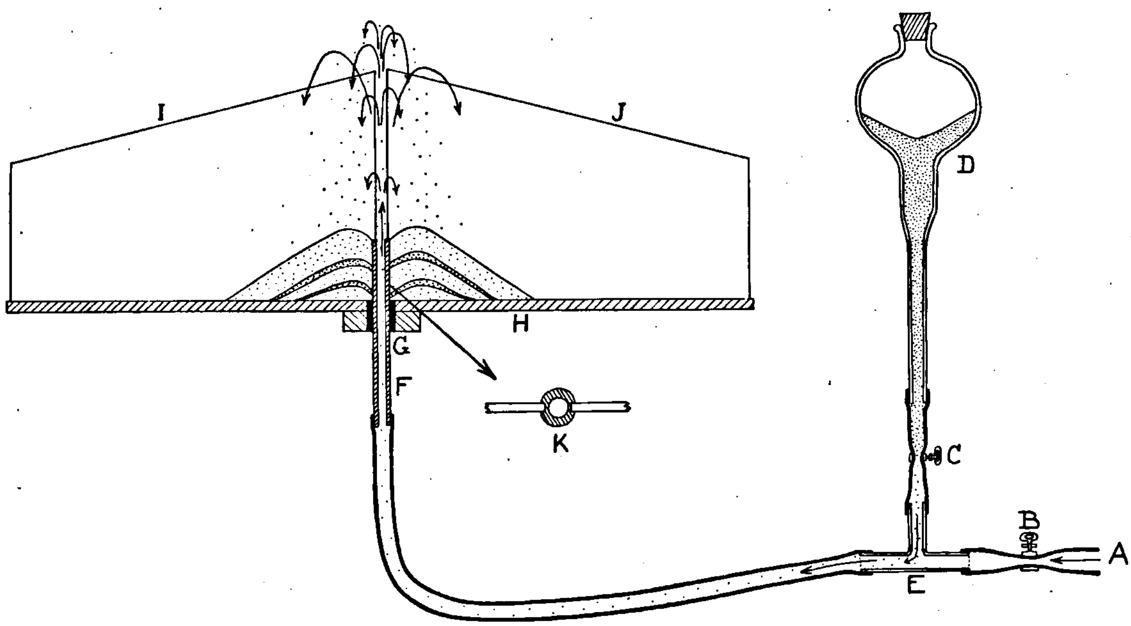


Fig. 1.

Diagram of the apparatus used.

The differences between this arrangement and those used by JUDD and LINCK are only small, but the advantages are that we can now imitate the gradual upward growth of the neck inside the volcano by pushing the blow pipe upwards. By pulling it down again the collapse of the crater after an eruption can be caused.

In one experiment lava flows were imitated by plaster of Paris and in another fine pumice was used by way of coarser ejectamenta. It is further worthy of note, that while the red powder did not influence the properties of the dune sand used (dark in the photographs) the white chalk powder was slightly adhesive. LINCK did not use loose powder but coloured sand. Although this has the advantage of marking the stratification more sharply and the panes of glass are not soiled, by our method we not only obtain layers with slightly differing properties but the powder is partly blown out between the sand. This produces a dust cloud that teaches us something concerning the slower movements of the eruption cloud after the speed has decreased so far that the grains are dropped.

V. DESCRIPTION OF THE EXPERIMENTS.

It is not necessary to describe all the 18 experiments separately. The essential facts they teach are the following.

1. Growth of a cone with constant strength of eruption.

In principle there is no difference whether we blow with a slight current that is only strong enough to throw up the grains a few centimeters or whether the maximum force available is used that spouts up the sand to nearly two meters above the table. In both cases the sand is built up in a circular mound around the blow pipe in the same manner as in LINCK's experiments. The only difference is the size of the mound, that is: the distance from the pipe at which the maximum amount of sand accumulates.

If the blow pipe is not raised the inner slope of the crater soon becomes so steep that all sand falling on it rolles down and is carried upwards again in the sand blast. The distribution of the sand is such, that the outer slope is still much less steep. This part and the crest go on growing upwards, but soon the crater has become so wide, that almost all sand falls back into it. A nearly stationary condition is then attained.

In general LINCK's experiments were carried on to this stage, while in our experiments the blow pipe was generally raised as soon as the sand began to roll back into the blow pipe.

If we now raise the blow pipe a few millimeters, thus imitating agglomeration in the volcanic cone and then renew the activity, the declivity of the crater immediately decreases on the inner slope, thus diminishing its diameter. Soon the rolling down of sand recommences in ever increasing volume with the growth in diameter of the new crater. The diminution of the diameter of the crater is followed by the addition of a new layer on top of the crest and on the outer slope. The thickness of this layer decreases with the distance from the crest in the same manner as for the under lying stratum. As a matter of fact the whole process is more gradual, than here described, sothat the growth of the new layer begins everywhere at the same time, but it is most swift in the crater, and continues longer on the crest and outer slope.

With each repeated protrusion of the blow pipe the cone grows upwards. At the same time the outer slope becomes increasingly steeper, on account of the diminishing thickness of the layers outwards. Finally the natural slope of the sand is reached. From thence onwards all sand added to the outer slope is in labile equilibrium, because it is built up steeper than the natural slope. Every now and again a small land slide begins and in its section carries down all the sand that had accumulated above the natural slope (above the spot where it begins) and deposits it in a steep delta at the foot of the cone in the natural slope. Fig. 2 illustrates this process. The photographs (especially fig. 3,

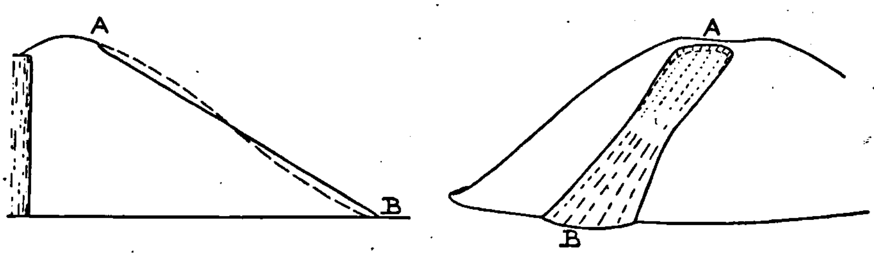


Fig. 2.

Land slide on model cone.

Plate 3, righthand side) show that the miniature volcanoes are highly symmetrical, in accordance with which the land slides generally begin on all sides at nearly the same moment.

It is obvious that the cone has now reached a stable shape, for it cannot grow any steeper. From now onwards the top grows in the normal manner, while the foot is added to by land sides. *Apart from the apex the cone has a straight profile.*

Several experiments were carried on until this stage was reached, but not much further as no new phenomena occur. The slight concavity at the foot is soon overlaid by the materials that slide down. The irregularities in the thickness of the layers are caused by the intermittant nature of the slides. Sometimes the slides were directed slightly away from the pane of glass sothat only the negative form is visible (fig. 3, Plate 1) [1]).

2. Cones formed by eruptions of varying strength.

By varying the strength of eruption we can build up almost any profile we wish. As large strato-volcanoes are practically always concave this shape was studied more extensively than the convex shapes.

[1]) When the size of a cone is small as compared to the diameter of the particles used, slight complications arise. This is not of importance in volcanoes and in our experiments as the particles are too small in comparison to the cones. (See F. M. EXNER [8])).

The following variations were made. A strong eruption was followed by eruptions of ever decreasing strength (fig. 1, Pl. 2). The order was reversed, the weak eruption coming first (fig. 2 and 3, Pl. 2).

The strength was varied from maximum to minimum and back again to maximum, or the other way about (fig. 4, Pl. 2, the successive strata do not show in this photograph, except the last one). A considerable cone formed by weak eruptions, was followed by a few strong ones and these in turn by weaker and a very weak eruption (fig. 5, Pl. 2). In all these cases a concave slope was produced that strongly recalls the slopes of natural volcanoes.

It is obvious that the profile we obtain depends largely on the duration of the various strengths of eruption. Thus a convex slope can also be produced by emphasizing the stronger eruptions (fig. 1, Pl. 3). This model is asymmetrical (it would lead too far to explain exactly why) but no new principles are introduced by this irregularity.

If the stronger eruption has only a slightly wider radius than the weaker one and is not too voluminous, the slope is not altered otherwise than by a slight rounding off at the apex (fig. 3, Pl. 1). A small cone can also be erected in a large crater (fig. 2, Pl. 1).

From these experiments it follows, that as long as the amount of material produced (in section, not in volume) is greatest for the weaker eruptions, a concave slope will be formed.

3. The influence of lava flows.

If a lava flow is produced low enough on the slope or is sufficiently fluid to reach the bottom of the cone, it will produce a slight concavity at the foot of the mountain (fig. 4, Pl. 4, at the lefthand side). If it is too viscous or starts too high up on the slope it will form an irregular, local convexity. Only a few thin layers of loose ejectamenta are needed to cover it up smoothly again and the natural slope of the latter is reestablished (fig. 4, Pl. 4, righthand side). On this photograph we see how this is brought about.

4. The influence of variations in size of the ejectamenta.

Although the natural slope of the fine pumice sand used in the experiments was similar to that of the sand, the grains behaved in a very different manner. It made no essential difference whether they were shot out separately or mixed with sand. In both cases the larger volume and mass of the particles of pumice caused them to make small pits in the sand enabling them to form a thin layer on the crest of the cone. The grains falling on the slope either rolled down to the foot or rebounded from the cone and were scattered over a relatively wide area. Those that rolled down the slope soon built up a thin veneer over the sand, that grew upwards until the cone was covered with a coating of pumice. As the panes of glass shielded off the section that appears on the photograph, only the first stage in the formation of this coating can be seen. It was even necessary to drop a few extra grains against the glass artificially to bring out the position in the photograph more clearly (fig. 1, Pl. 4).

5. The influence of collapse after an eruption.

Prof. UMBGROVE kindly pointed out to me that in real volcanoes the strata generally appear to dip away from the crater, sothat the inward dipping layers of the experiments seem to be absent.

This must be attributed to the fact that after an eruption the inside of the crater is known to collapse into the volcanic pipe, when it has not been filled with lava or loose ejectamenta (cf. after the Vesuvius eruption of 1906). An attempt was made to imitate this phenomenon in the experiments by pulling back the blow pipe a few cm. The result, that may be seen in fig. 2—4, Pl. 3, closely resembles the configuration of many craters. It may be thought that this phenomenon can only be produced once in the history of a volcano, or only again after prolonged activity.

Therefore the collapsed crater of fig. 1, Pl. 4 was used for the formation of a few new layers fig. 2, Pl. 4, followed by a new collapse fig. 3, Pl. 4.

Although in the section we see that the lower layers dip into the crater it is obvious that this might escape the attention of an observer standing on the rim. The examination of such a crater might lead to the conclusion that all the strata dipped away to the outside.

6. The cone formed by explosive type of eruption.

In order to ascertain whether a more sudden explosion of the materials would form a different type of cone an experiment was made in the following manner. The sand was carefully introduced into the top of the blow pipe, filling it to the brim. Then with a bicycle footpump air was forced up through the rubber tube.

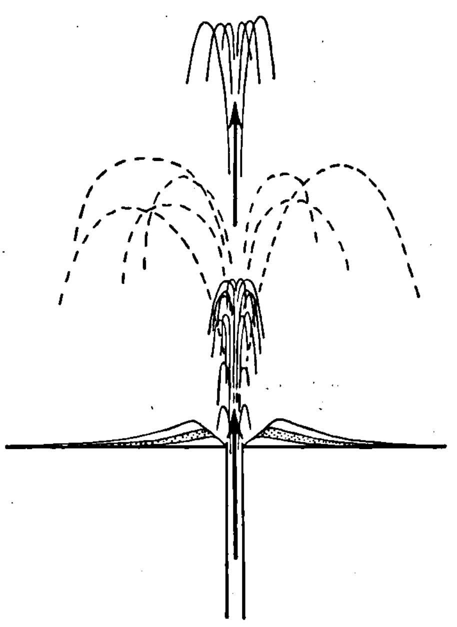


Fig. 3.

The three successive types of eruption when using the bicycle foot pump.

The sand rose up in a more or less solid fountain until the compressed air reached the opening. With a distinctly audible pop the air expanded and sent up a volume of sand that spread out in an umbrella shaped figure falling down over a wide area around the crater. If the amount of air was sufficient, a relatively violent eruption of short duration followed in every way identical with the more prolonged but weaker eruptions of the other experiments. The greater the volume of air used, therefore, the more the eruption resembled those of the other experiments. Fig. 3 shows the three phases combined in a rough sketch. It will be seen from fig. 5, Pl. 3, that the distribution of the sand in the cone is entirely different to that in the other experiments. The maximum thickness occurs directly beside the blow pipe and decreases much less suddenly, thus reaching to a greater distance from the vent. Immediately with the first layer the crater obtains the maximum slope for the sand used. Slight variations in the strength of the eruption naturally occurred with this apparatus. The decrease of thickness for the products of one single eruption appears to be a straight line and would lead to a cone with a straight slope ending abruptly against the bare table. The variations between the 3—5 successive eruptions used to build up each of the layers of sand, result in a slightly concave section. The resulting slope of the volcano was therefore also slightly concave. For this reason it takes somewhat longer with this eruption type after the natural slope of the sand is already reached at the top before it is also attained for the whole slope. When this stage is at last reached, however, the cone has gradually assumed practically the same profile as in the other experiments. In the illustrated experiment a collapse was caused, followed by renewed activity that soon reestablished the old shape. It should be noted in studying the photograph that leakage of sand along the blow pipe has caused slight irregularities. To these no attention should be paid as they only influenced the photographed section and have no parallel in nature.

No land slides are formed with this type of cone-construction when it has reached the natural slope of the sand, as the greater force with which the large volume of material falls back onto the volcano, causes it to assume directly the natural slope of the sand.

7. The relation between height of eruption and width of scattering.

If we measure the radius of the crater (that is the distance from the centre to the circle on which the sand is piled up in greatest thickness) and the corresponding height of the eruption, we find that the latter is always 10 to 15 times as large. In fig. 4 the two values for the four cases measured are plotted against each other.

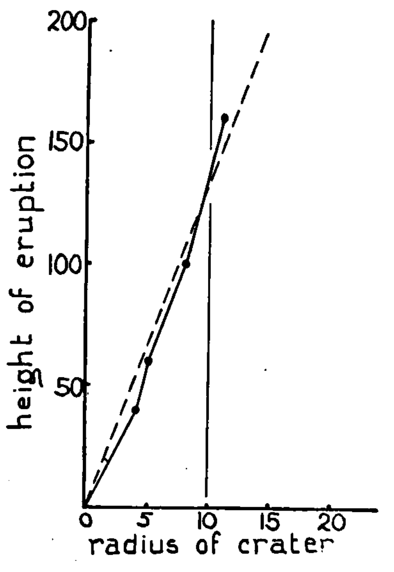


Fig. 4.

Relation between height of eruption and width of scattering.

VI. INTERPRETATION OF THE RESULTS.

Here, as in all experimental work in the field of geology, great care must be taken in the interpretation of our results. The complexity of nature is in no wise attained in the laboratory. This has the advantage that we can study the simple principles without being disturbed by the countless complications that tend to obscure each individual case in nature. Before denying the value of experiments on account of their too great simplicity, we should remember that our conceptions of natural phenomena are also much simpler than what actually takes place.

Nevertheless these simple ideas may be incorrect. If, however, our simple experiments confirm the simple conceptions then we know that at any rate the foundations of our theory are firm. A theory based on elements that are proved to be correct by experiments, has greater vitality than one based on apparently simple and straightforward, but unproved ideas.

1. To which type of volcanic activity can our experiments be compared?

It is of course obvious, that our experiments can only teach us something concerning the construction of cinder cones and strato-volcanoes, that is of volcanoes in which lava flows play a subordinate part. It is also evident, that no figures can be deduced from the experiments as to the declivities in nature, as the materials have different properties. With the series in which vacuum cleaners were used, a large volume of gas is extruded in which a comparatively small amount of loose ejectamenta are carried along. This corresponds to the "Perret-phase" of eruptivity, the type-eruption of which was the Vesuvius eruption of 1906.

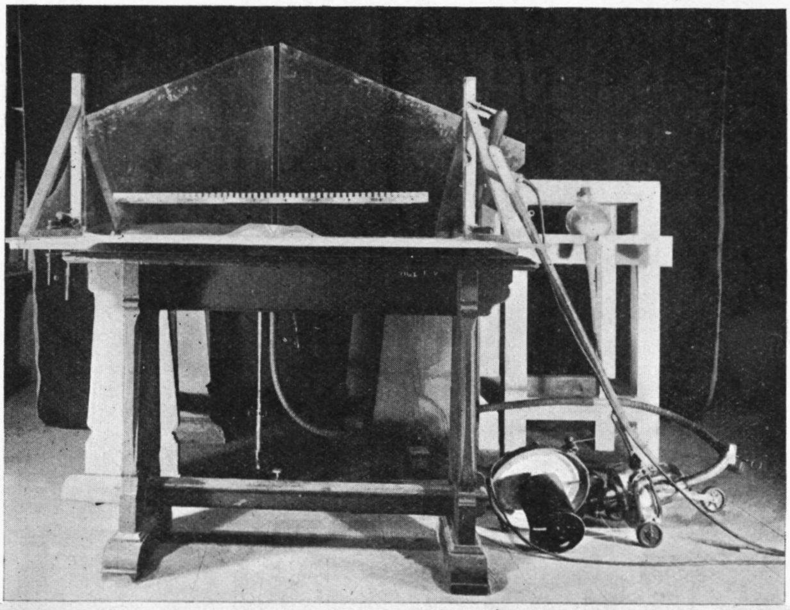
The experiments in which a bicycle pump was used are not a strict parallel to any type of natural eruption, but they come fairly close to an explosive eruption in which a plugged vent is suddenly opened for a short period of violent activity. The principal difference is probably the too strict separation of sand and air and the constricted shape of the blow pipe that is not altered by the force of the eruption.

Although the two types of activity used, distribute the materials differently, the cones that finally result are essentially similar. It would therefore seem probable that in nature, where the types of eruption fall somewhere between or near the experimental extremes, the result will be comparable to those we obtained.

2. Influence of the form of the crater.

It might be maintained that the shape of the blow pipe and crater must have a great influence on the shape of the eruption and therefore also on the distribution of the ejectamenta. This is hardly the case.

The shape and depth of the crater do not influence the eruption in the least, only the piling up of the sand when it drops down. But



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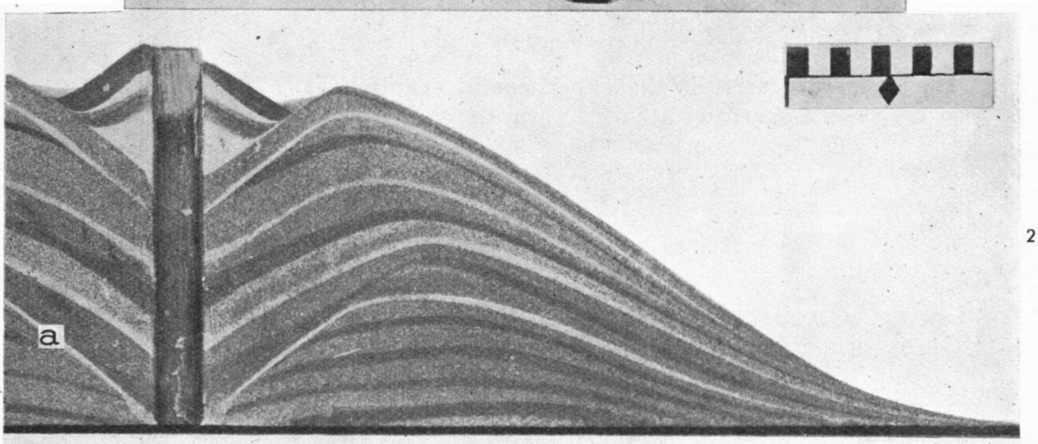

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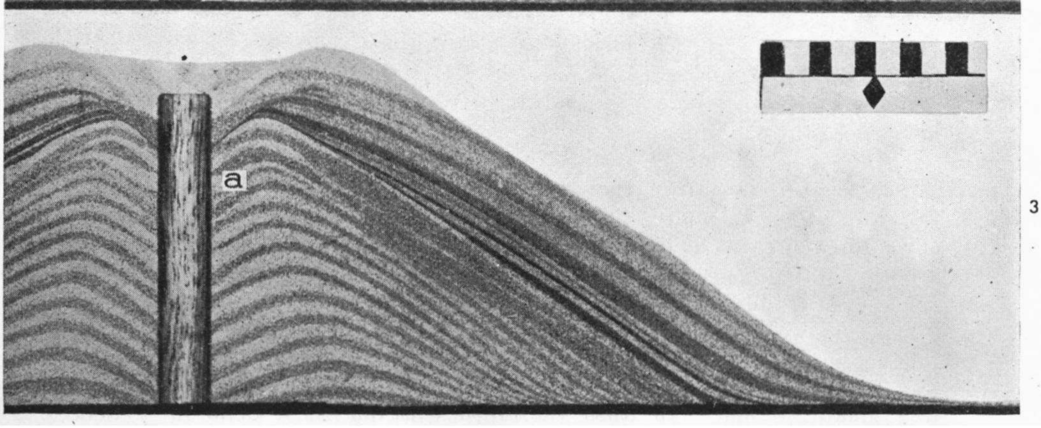

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Fig. 1. Apparatus. Compare textfigure 1.

Fig. 2. Cone built with maximum force of eruption (a = first layer after first extrusion of blow pipe), with secondary cone in crater, the result of very weak eruptions. On right of latter first slide.

Fig. 3. Cone built with middle force of eruption (35 cm). With eleventh dark layer (a) sliding began. Following set of eruptions, beginning with very dark layer, four times as high. Only slight concavity. Experiment stopped after first slide (on right) took place (only negative form of slide is visible).

even the shape of the blow pipe has only a slight influence. Thus a conical blow pipe was used in an attempt to widen the distance of scattering, that is shown to scale in fig. 5. The eruptive column was seen to rise centrally from the blow pipe and practically no change in the shape of the eruption or of the width of scattering ensued. In part of the experiments in which the angle of the cone was even less, there followed a slightly greater scattering but not sufficient to alter the shape of the resulting cones. We may therefore safely conclude that the shape of the crater and pipe do not alter the resulting cone materially.

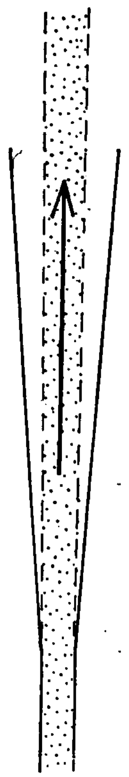


Fig. 5.

Section of conical blow pipe with accompanying eruption, ½ natural size.

3. The influence of wind during the eruption.

The path of larger ejectamenta is not altered by wind but the finer particles, especially ash, are carried along by wind during the eruption. Strong winds will therefore have the same result as if the eruption were somewhat more powerful. Part of the asymmetry of the cone fig. 1, Pl. 3 is probably due to a current of air playing in the laboratory during the experiment.

4. The force of the experimental eruption as compared with natural eruptions. The scale of the experiments.

Direct quantitative comparison between the force of the eruptions in the experiments and in nature is not possible on account of the different circumstances. In nature condensation, contraction through cooling, difference in atmospheric pressure at different levels, are factors that cannot be imitated experimentally. As these influences, however, are too small to alter the course in the air of the lapilli and bombs, they will not seriously alter the results. On the other hand the dark clouds of ash and condensed vapour that form the visible eruption cloud in most volcanic eruptions obscure the view of the more massive particles. For this reason, it must generally remain unknown to what height the latter are thrown up.

In the experiments clouds of dust and powder for colouring the sand rose up, imitating the eruptive cloud. These frequently attained to two, three or more times the height of the sand grains, before spreading out in a broad, sluggish mist in the laboratory. But as already stated a comparison for the finer materials is not allowable. As the eruption clouds of larger eruptions rise to heights of many kilometers we will assume that the greatest height reached by the bulk of the larger ejectamenta is seldom more than 1000—2000 m. In our experiments the average height to which the grains were thrown up was about 50 cm. We were therefore working to a scale of 1:3000. As the model cones were built up to heights of 10—20 cm their size

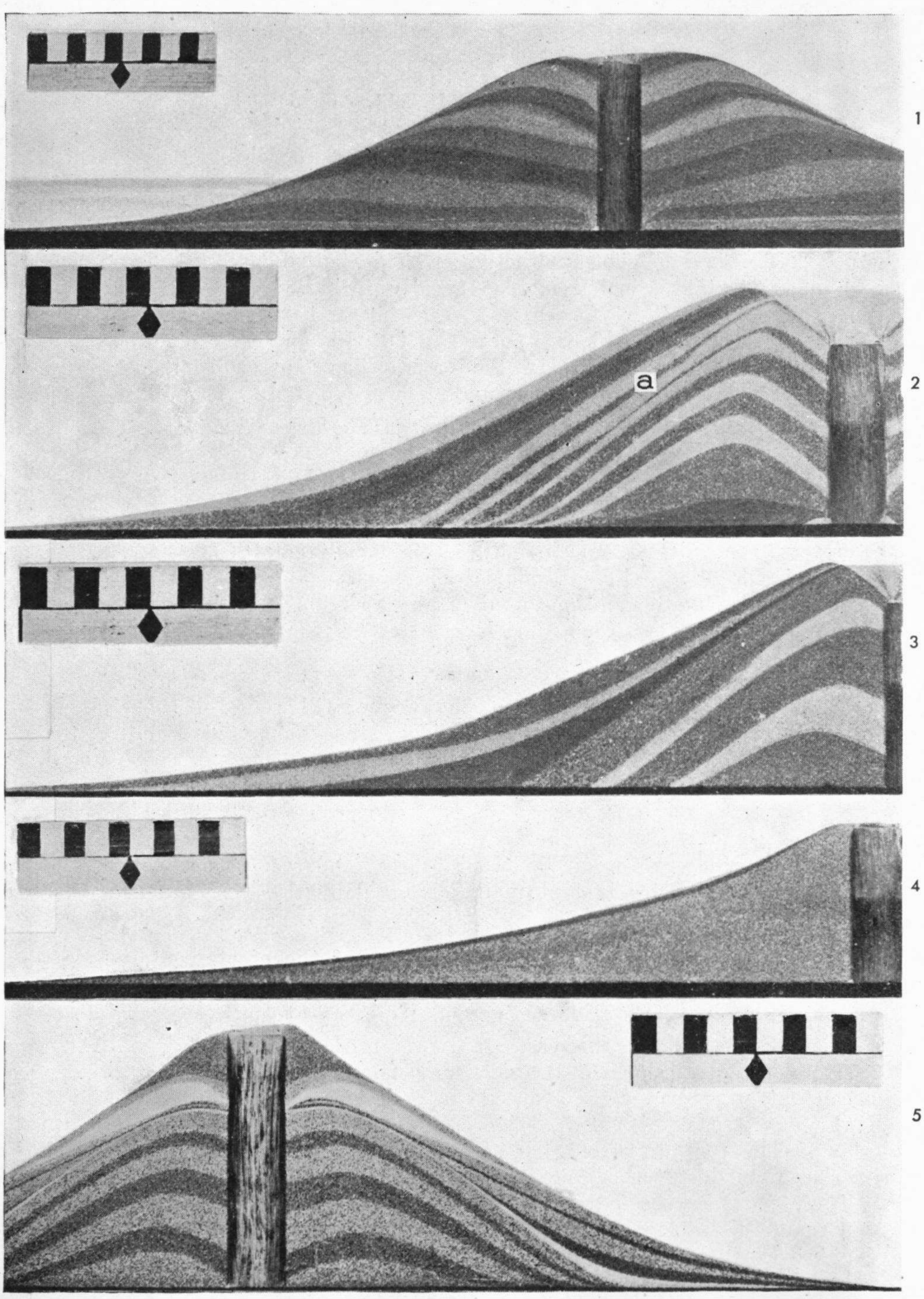


Fig. 1. Cone built with decreasing force of eruption.

Fig. 2. Cone built with constant weak eruptions until red layer (a). Beginning with next white layer, increasing force of eruption for each successive layer.

Fig. 3. Cone built with constant weak eruptions, the last two layers but one with increasing force of eruption, last layer with middling force.

Fig. 4. Force of eruption varying constantly from min. to max. a great number of times.

Fig. 5. Constant weak eruptions. First white layer marks a series with maximum force, second white layer again weak eruptions. Cap built by very weak eruptions. A slide has carried away left top of crater rim.

would correspond to volcanoes of only 300—600 m. These numbers are of course only a first approximation, but they clearly demonstrate that only the initial stages in the construction of a volcano were reached in the experiments. In order to imitate a true volcano the experiment would have to be carried on to at least 4 times the size we reached or 64 times the volume. (With the methods used this would have occupied 4 days of continual activity). This, as will presently be shown, is an important conclusion that greatly influences the interpretation of the results.

The size of the blow pipe was about 10 mm corresponding to a neck of 30 m diameter. In the cases when our eruption was only 10 cm high, the blow pipe would correspond to a volcanic neck of 150 m. Although smaller, the resulting cone was identical to those of the stronger eruptions. This shows, that it is of no consequence that our blow pipe was somewhat too small as compared to the average strength of the eruptions.

The diameters of the craters range from 3—15 cm, for the collapsed craters from 10—20 cm. In nature this corresponds to 300—600 m for collapsed craters, also reasonable dimensions.

The strongest eruptions used reached heights of 160 cm and therefore represent exceptionally violent eruptions for the scale used.

5. The influence of flows of lava.

Flows reaching the bottom of a cone will round off the angle between cone and substratum. The larger the volume, the fluidity, the lower the point of eruption, the smaller the cone, — the more pronounced will be the influence. Vicous flows that come to a standstill on the slope will cause irregularities and convexity of the profile. Viscous lava is generally accompanied by explosive action. In the cases therefore in which lava woud be most apt to render the slope convex, its temporary influence is continually obscured by the loose particles that reassert their natural slope.

6. The influence of variation of size of the ejectamenta.

Our experiment shows that the influence of larger blocks is to soften the sharp angle between cone and substratum. As soon, however, as the amount increases, a new profile is established with the straight natural slope of the new materials. A markedly concave slope can therefore never be caused by the scattering of particles of varying size.

When the size of the particles in nature decreases to that of sand or even to dust (ashes) new elements are introduced into our problem. These particles can be carried along by currents of air such as occur without the interference of an eruption. They are caught up and spread out over vast area's by the strong winds generally prevailing in the higher strata of the atmosphere. The ascent of the air and gasses above the erupting volcano in the experiments and in nature goes up to much greater heights, than that to which the larger particles are shot and carried. It would lead us too far to attempt to analyse these

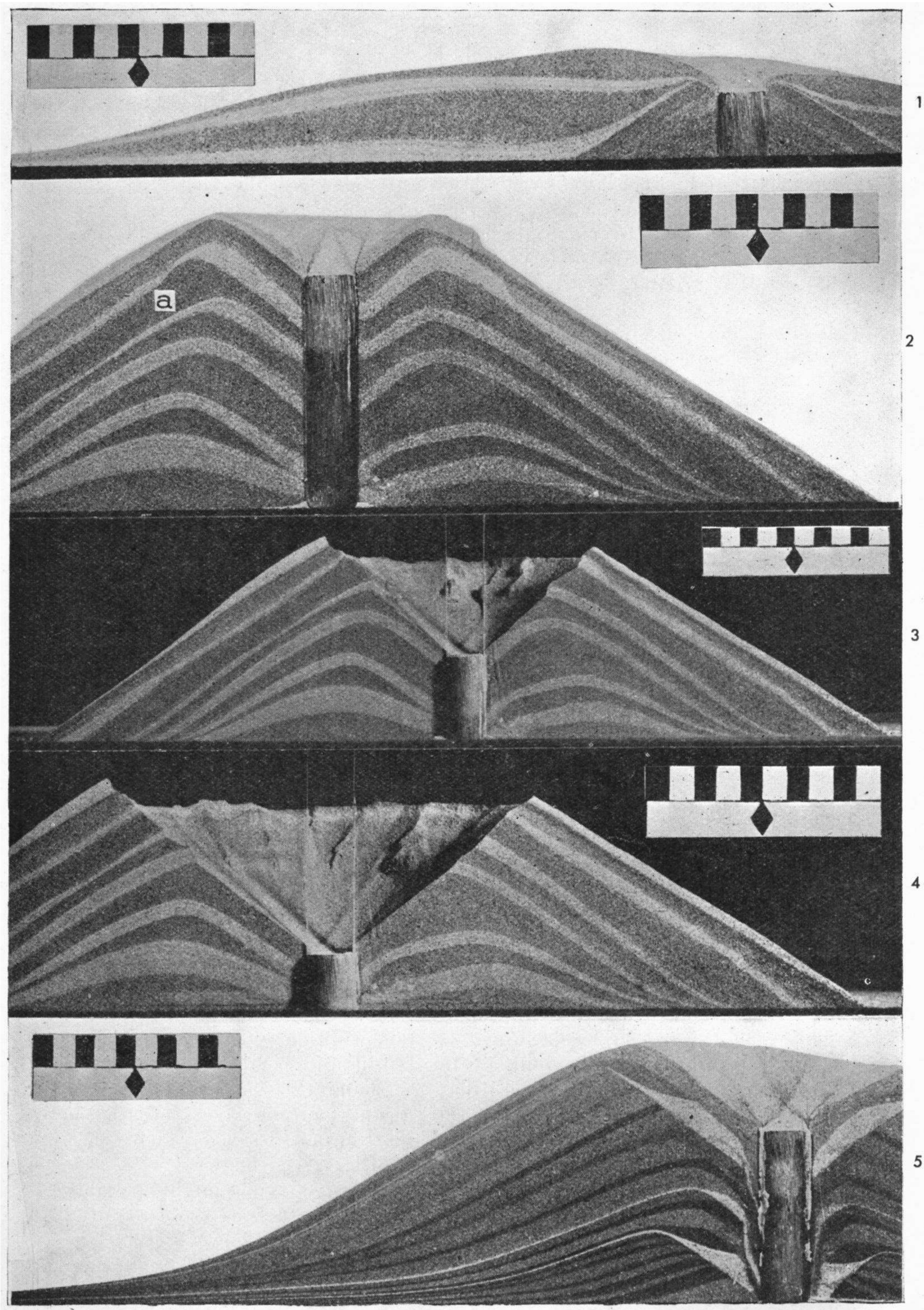


Fig. 1. Cone formed by very weak eruptions followed by three eruptions of max. force (white, dark, white). Cap formed by eruptions of decreasing strength.

Fig. 2—4. Cone formed by eruptions of constant force, followed by two successive collapses of the crater. On both sides first slide in (a).

Fig. 5. Cone formed by eruptions of explosive type (with bicycle foot pump). First white layer after first extrusion of blow pipe. Slight collapse of the crater, followed by third white layer and dark and gray layers with growing crater pipe.

complicated aerodynamical problems. (Thus the experiments already showed a strong downward current outside the eruptive column, carried along by the dropping grains. On reaching the cone it rolled down the slope and spread out over the country beyond the foot). Suffice it to note that these upward movements, aided by vortexes and turbulences are able to move the ashes along. This finer material does not follow the simple rules observed by the larger particles as to distribution around the vent. On the whole we may assume, that they drop in a layer that is thickest close to the crater and decreases in strength very gradually to distances far beyond what is still counted to the volcanic cone.

7. The influence of variations in the force of the eruption.

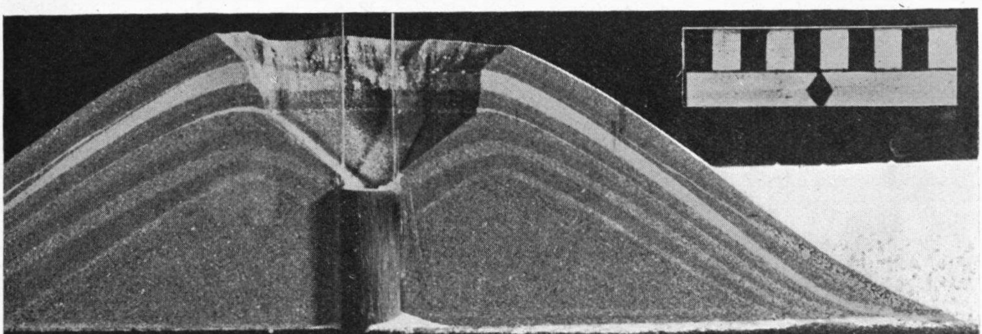
The experiments demonstrate with remarkable clearity that variations in the force of eruption may produce both concave and convex slopes. To produce a slope that is convex over most of its length, the strongest eruptions must greatly predominate over the weaker, not only in volume but even in section. This is certainly a highly uncommon case. In the case that the weakest eruptions predominate in section the slope is convex and similar sections result when the middle force of eruption predominates (in section). In the latter case there must be occasion for the volcanic pipe to grow upwards in the cone, otherwise the products of the weaker eruptions all fall back into the crater.

There is one important restriction to the influence of variations, namely, that the cone must not be too large for the strongest eruptions to be able to pile up the maximum thickness of their products close to the foot. If a considerable cone has first been built up and the eruptions following are not sufficiently stronger, they will have practically no influence on the shape of the profile.

As soon as we introduce our rough estimations of scale into the discussion it transpires that the slope of volcanoes of middle size are already too large to be influenced directly by any but the strongest eruptions possible. In the case of a volcano of 1000 m high the maximum thickness of a new layer that is to render the slope concave must be situated at least some 1200 m from the centre. This would require a height of the eruption of about 12 times as much or some 14000 m (see fig. 4). This height is sometimes attained by the eruption cloud, but must be quite exceptional for the bulk of the lapilli and bombs. It is only of these larger materials, however, that the amount is sufficient to be of material importance. Not only is the thickness of the layers of ash too small to have much influence, but the distribution described above does not favour the production of concave profiles (see fig. 6).

The second type of eruption, the explosive type, might possibly hurl sufficient amounts of fragments to distances such as those required to render the slope concave. Experience has thaught, however, that the explosive type, of sufficient force for the bulk of materials to fall at the foot of the slope, occurs so very seldom that the influence on the sections of larger volcanoes cannot be appreciable.

As exceptionally violent eruptions tend, moreover, to destroy the top of the volcano by the formation of a caldeira, they cannot be held responsible for the concavity of fully developed cones.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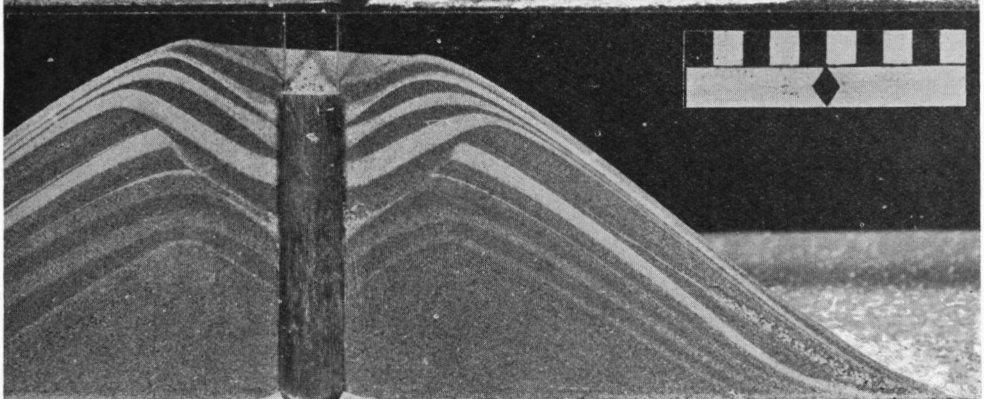
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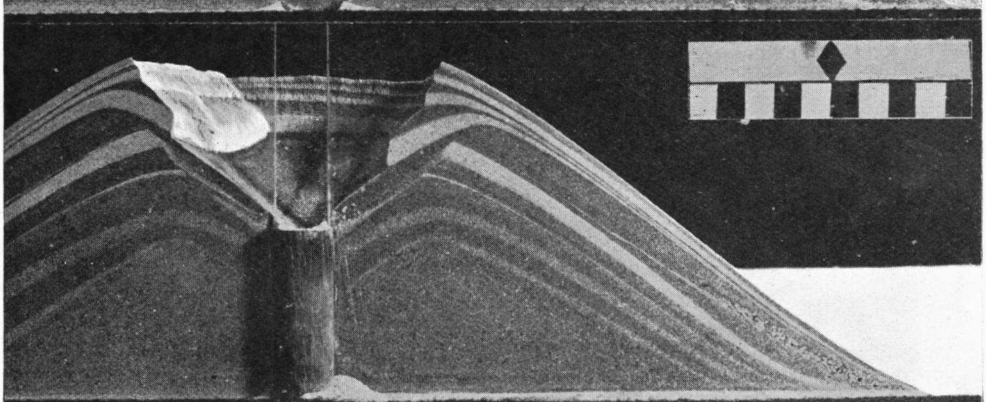
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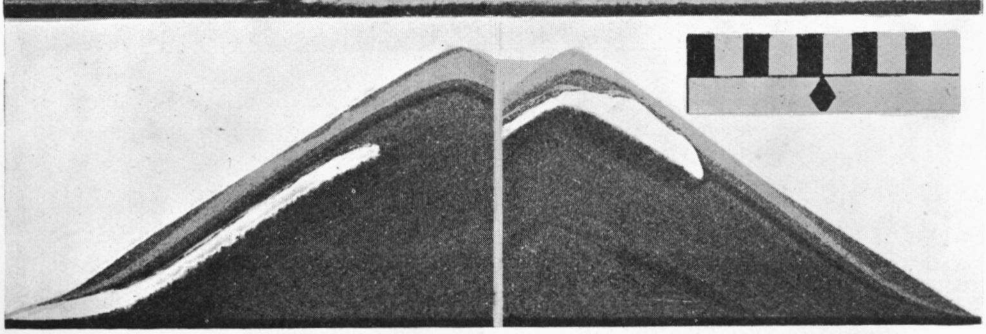
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Fig. 1—3. Cone formed by constant strength of eruption, followed by collapse of crater (fig. 1), renewed activity (fig. 2) and finally again collapse (fig. 3). Layers of pumice sand, visible in crater (fig. 1), in section and on table (fig. 1 and 2).

Fig. 4. White plaster of Paris imitating lava flows. On left reaching foot, on right stopped on slope of cone. Subsequent layers soon obscure the influence of the flows.

A separate comparison of our experiments with those of LINCK is not necessary after what has already been said about the latter.

VII. GENERAL CONCLUSIONS.

Viewing the results of the experiments in connection with what is known of natural volcanic activity the following general conclusion may be drawn, as to the *constructive* activity.

In volcanic cones in which loose ejectamenta predominate over lava flows the profile tends to be built up as a straight line, corresponding to the natural slope of the materials. Variations in the strength of the eruption may cause convex slopes, but practically always tend to produce concave profiles. Variations in the size of the fragments has the same influence but in a very restricted degree. The relative amount of gas, even when small enough only to cause an initial explosive eruption without a gas phase, does not influence the shape of the resulting cone, although the particles are scattered differently in the latter case. Volcanoes of upwards of 1000 m height are built up with a straight slope irrespective of the type and force of the eruption. Even the most forcible eruptions are no longer able to scatter the larger amount of the particles close enough towards the foot to round off the angle between cone and substratum. The construction of such cones is entirely dominated by the natural slope of the materials. Although volcanic ash falls even at distances far beyond the foot, the absence of a pronounced maximum thickness anywhere in the section and the relatively small bulk are both reasons why the angle between cone and substratum is not rounded off (fig. 6).

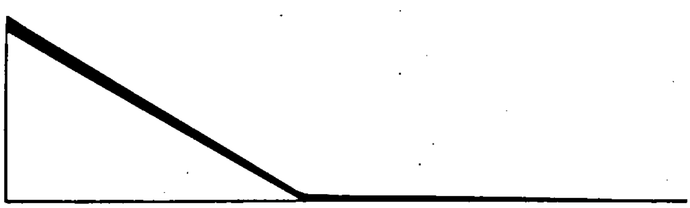

Fig. 6.

Failure of layers of volcanic ash to round off angle between cone and substratum.

Although the scattering tends to produce a crater with a rounded off rim and strata dipping inwards, the collapse of the crater produces a sharp edge. The observable outward dip of the strata may be in part an optical delusion in some cases.

The crumbling of lava plugs produces glowing clouds. These will have the same influence as larger loose ejectamenta.

The concavity of the profile of most volcanoes, especially the larger examples must therefore be attributed to secondary causes. This is all the more probable as it are especially the larger cones that present the most pronouncedly hollow sections. If the scattering were the principal cause it would be the other way about. A study of the submarine sections of a number of East Indian volcanoes that rise from a fairly deep and flat sea floor, led the present author to the same conclusion. For details the reader is referred to the forthcoming publication in the Reports of the Snellius Expedition mentioned. Suffice it to point out that only the dry cones of more than 1000 m height are distinctly concave, approaching to horizontal towards sea level, but that even for these the submarine slope is of the same order of steepness as the upper reaches of the dry part and practically straight.

The influence causing the concavity of large volcanoes is thus proved to be restricted almost entirely to the subaerial part and can therefore be no other than erosion.

Leiden, December 1933.

Note. After the manuscript of this article was ready for print I came across the paper by J. STINY: Zur äusseren Gestaltung der Feuerberg-Auswurfmassen. Centrallblatt für Min. etc., Abt. B, 1933, p. 379—389.

In this paper experiments are described in which quantitative data were procured by the same methods as those used by LINCK. Although an elongated blow pipe was used in some experiments and its importance appreciated, the objections against LINCK's experiments may also be raised in connection with STINY's results. The influence of the size of the particles, of the cones and the diameter of the blow pipe and also of the force of the eruption were analysed. As every single cone in nature, and especially the larger ones, are built up under strongly varying circumstances and as these are not strictly parallel to those of the experiments, STINY's results are more of theoretical than of practical importance. My own experiments show, moreover, that *variations in the strength of the eruption and growth of the pipe* during the building up of a volcano have a far greater influence.

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