Geology. — *On a new Basis of Solution of the Caldera-Problem and some associated Phenomena.* By C. G. S. SANDBERG D.Sc. (Communicated by Prof. Dr. G. A. F. MOLENGRAAFF.)

(Communicated at the meeting of November 26, 1927).

The various attempts at solving the Caldera-problem are governed, generally, by the principle of seeking an explanation :

a. of the mode of causation of a large volcanic rim enclosing, partly or entirely, a more or less flat bottom (the caldera), the diameter of which is so disproportionately large in comparison with that of the presumed magmatic conduit, that the said enclosing rim cannot reasonably be admitted to represent the primary product of eruption of the said narrow conduit ; and

b. of the phenomenon of the revival of volcanic activity at or near the places of former action, after a longer or shorter period of rest.

It is the intention of the writer to indicate here only a plausible solution for the problem formulated sub *a.*, whilst accepting for the present as an empirically well established fact that mentioned sub *b.*

When considering the various studies of the caldera-problem, it appears, as far as I know, that they are governed by the following presumptions, viz. : that a volcanic cone, $b + c$, is (assumed to have been) built up round and above an eruption-centre *a.* which is, more or less arbitrarily, taken as the most likely one, and which is situated at the top of a volcanic conduit *p* (Fig. 1). Subsequently, part of the cone which would have been formed thus, i.e. the part marked *b.*, is supposed to have been destroyed, leaving

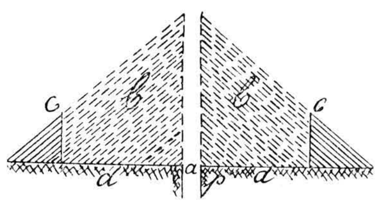

Fig. 1. Schematical section of caldera according to current conceptions. a = centre of eruption; p = Magmatic conduit or volcanic pipe; d = caldera bottom; b = vanished part of presumed original volcano; c = rest of presumed original volcano, the caldera rim.

only a (caldera) rim *c* and a *grosso modo* flat bottom *d*. In other words, the problem as it was and is posed is based on the presumption that the eruption(s) from a magmatic conduit *p* with an eruption-centre *a* caused a volcanic cone $b + c$, and its solution was and is consequently governed by the search for a plausible explanation of the disappearance of the part *b* and the causal formation of the vertical enclosing wall and the *grosso modo* flat bottom *d*, the diameter of which so abnormally exceeds that of the presumed eruption-centre *a*. (v. HOCHSTETTER, STÜBEL, VERBEEK, DALY, DUTTON, CHAMBERLIN, WING EASTON, ESCHER a.o.).

R. A. DALY (1) expresses the current conception in the following words: "If the actually exposed "necks" of the world indicate the maximum size of central conduits, the vents beneath calderas must have cross-sections much smaller in area than the floor of the corresponding great depressions. The writer is in fact, inclined to make this the criterion for explosion craters from calderas."

The directions in which the solution of the problem have been sought may consequently be classified in the following catagories :

1. *The explosion theory*. The part *b* of the cone is assumed to have been blown away subsequent to an extraordinarily heavy explosion which is supposed to have emanated from the eruptive centre *a*, or from a point lower down the conduit *p*, part of the débris falling back into and so partly filling up the large opening thus caused, and so giving rise to a more or less flat floor.

2. *The subsidence theory*. Part *b* of the cone would have subsided along vertical or semi-vertical peripherical fault-planes, leaving only the rim *c*, subsequent to having been undermined below or above its base (somewhere near *a*) all round the conduit *p* or/and the conduits' upper extension, which we shall henceforth name the *cone-pipe* ;

3. *The re-fusion-backflow theory*. Some time after the erection of the cone $b + c$, by ejectamenta from *a*, a new eruption of incandescent gas-saturated magma would have liquefied the part *b*. Subsequently to a following heavy paroxysm, part of the re-fused cone would have been blown away, the rest flowing back to deeper regions through the conduit *p* and leaving only a rim *c* round an enlarged, *grosso modo* flat "depression" *d*.

As to the *last mentioned theory*, it may suffice to refer to WING EASTON's refutation of it (2), to which may be added that e.g. the facts observed during the Vesuvius eruption (3) established that such partial re-fusion of the cone may actually occur. They were realized when the rising magma reached its highest level in the cone-pipe. Yet instead of flowing back into the conduit the incandescent magma discharged laterally, breaking through the sides of the cone. The causal formation of a, *grosso modo*, vertical inner wall, a feature which cannot be causally connected with such backflow or discharge, as WING EASTON has pointed out, did not occur.

Again, with regard to the *explosion theory* it may suffice, to avoid repetition, to refer to WING EASTON's refutation, which may be summarized in his words : "The causation of a vertical inner-wall (of a caldera) subsequent to an explosion is certainly *possible*, locally ; yet it is not at all clear why this should necessarily occur, and then nearly always practically along the entire inner-circumference." (My translation from (2) p. 71.)

B. G. ESCHER's recent experiments (4), which only remotely touch the caldera-problem, have not weakened this conclusion in the least; besides no structure comparable with that of a caldera with its characteristic features was realized in the course of these experiments.

Let us now consider the *subsidence theory*. A very sharp distinction should always be maintained between caving in, gradual crumbling or sudden collapse *(écroulement)* of the enclosing wall, the rim, with subsequent lateral *enlargement* of a pre-existent "depression" and the causation of such a large space through *a.* subsidence (falling in) or *b.* down-throw of a superstructure, presumed to have been pre-existent.

Although different in principle, these phenomena have not always been rigorously differentiated by various students of the caldera-problem. (H. RECK, R. A. DALY and others).

Now as to the conception of caldera-formation by gradual crumbling or caving in of the rim-wall, there seems to be little doubt that WING EASTON's conclusion will be generally endorsed viz.: It seems natural that even a normal crater floor (the diameter of which should be identical with that of the orifice of the conduit) may come to exceed its theoretical dimensions through downfalling, explosion or perhaps re-fusion, but that would not transform such a crater into a caldera (the diameter of the Idjen-caldera is 16 km.; that of the Ringgit 21 km.). Besides they are characterized by very steep, often vertical inner walls (vide also V. WOLFF (5) *S*) which may attain a height of 1000 m (Rindjani) (Raoeng, Gendeng-Idjen, Tenger over 500 m). Very frequent also is the occurrence of a flat bottom sometimes called "sandsea" (Tenger, Slamet, Raoeng) [1])."

On the other hand we cannot possibly endorse WING EASTON's remark immediately following, viz.: "By these characteristics they (the calderas) are distinguished from normal craters", as will be shown below.

Since, therefore, we may discard the adequacy of the contention that caldera *formation* (not *enlargement*) may be caused by gradual crumbling or caving in of an encompassing wall, then the sole current theory which still remains to be tested is that of such causation as a product of subsidence *(effondrement)*, or of down-throw.

We have already mentioned that the caldera-structure is characterized by, among other things, a very steep, generally vertical or semi-vertical wall when not modified, secondarily, by denudation. We have also given some examples, which could be multiplied *ad libitum* (Kilauea, Barren Island Monte Somma, Knebelcaldera, Batoer, Fogo-Island etc. etc.)

This characteristic is not restricted even to terrestrial calderas, it is inherent also in lunar calderas.

The evident planetary nature of the said characteristic justifies the conclusion that it is primary and that it constitutes a genetic feature of the caldera-structure.

If this conclusion holds good it would exclude the admissibility of any

[1]) The double sound *oe* in Dutch is pronounced like the English *oo* in "poor".

of the current attempts at solving the problem, which one and all attribute the caldera-occurrence to a secondary origin.

Apart from this general conclusion, however, we shall analyse the theories sub. *a.* and *b.*, beginning with WING EASTON's.

It seems quite impossible to admit now that, before extruding vertically, the gas-channels which WING EASTON requires to produce his cells of undermining and which would have emanated, *grosso modo,* from an eruption-point *a* (see Fig. 1) would develop per se in lateral direction to such an extent as would be necessary for the production of calderas with dimensions such as are mentioned by WING EASTON himself (see ante p. 181). On the other hand it is also clear that this *impasse* in his theory cannot be overcome by transplanting the assumed point of emanation of these super-heated gas-channels to a proportionately deeper level of the magmatic conduit, as this would virtually amount to enlarging the diameter of the said conduit. In whatever way we attempt to conceive this process of honeycombing the basis of an (assumed) volcanic superstructure, this causation of cells of undermining, it must seem extremely improbable that subsequent subsidence of the (presumed) superstructure would *eo ipso* cause the remaining portion (the rim of the caldera) to be bordered by vertical walls which appear very strongly to constitute or to have constituted one continuous vertical plane. (Fogo Island St. Paul, Barren Isl., Monte Somma, etc. etc. See also p. 181. W. EASTON).

Finally it is extremely doubtful whether well established instances of such a mode of caldera-formation can be furnished.

Now, as to the assumption of caldera-formation by downthrow, it must be admitted that F. A. PERRET's studies of the Vesuvius eruptions (3) showed, among other things, that a sudden subsidence (of part of the foot of a débris-cone) may cause an opening, which might happen to be cylindrical, and to be bordered by a very steep conical wall (l.c. p. 117—118). Such a phenomenon, however, could occur only where a void was pre-existent below the subsided mass, of a size at least equal to that of the volume of the subsided mass. Now, as long as it cannot be shown that such a void must necessarily exist (or be formed in course of time) below a volcanic cone, and that the part concerned of the superstructure of the (presumed) orginal volcano must needs subside therein (sometimes perhaps by jerks *(par saccades)* and along concentric planes), so long will the calderaproblem remain unexplained on the basis of this theory, and its *quasi* solution simply means a substitution of the problem for other questionable presumptions regarding those deeper parts of our globe, of which still less is known to us with any degree of certainty.

Moreover we would emphasize that, in respect of the downthrow established by PERRET (l.c. p. 117—18), *the diameter of the incandescent magma-column then in course of ascension, in other words the diameter of the conduit, was at least equal to and most probably even larger than that of the produced conical subsidence with its semi-vertical inner wall.*

PERRET's observation cannot be invoked, therefore, in support of the subsidence theory, since the latter is based on the premise that the diameter of the magmatic conduit is *much smaller* than that of the subsided area.

On the mechanism of volcanic-cone building.

If now we may reject as untenable such conceptions of the origin of calderas as imply a secondary cause for their occurrence, then the question arises which part of a volcanic structure would be characterized, *genetically*, by those, *grosso modo*, vertical inner walls which typify among others the caldera occurrence. In order to solve this question we will examine the mode of formation of, say, a strato-volcanic-cone ; identical considerations apply to other types of volcanic cones, such as lava-domes *(Schildvulkane)*, among others. For convenience sake we shall take the form of the crater, which will generally be identical with that of the exit of the conduit at the base of the cone, to be circular, (though Askja is rectangular ; Tjiremai is oval ; the Barren Island volcano is circular ; etc.) See Fig. 2.

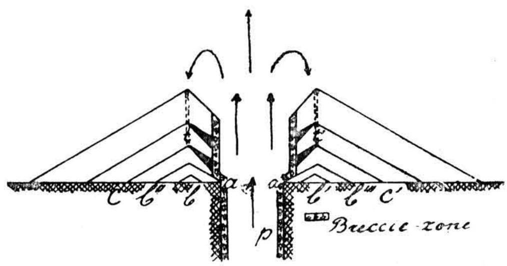

Fig. 2. Schematical vertical section of the mechanism. of volcanic-cone formation.
p = Volcanic-pipe (conduit) ; aa' = eruption-centre ; bb' etc. = volcanic-cone.

We may readily conceive that a volcanic eruption emanating from a conduit p will cause the ejectamenta to accumulate round its opening aa' in the form of an encompassing cone, a rim, bb'. Under identical conditions for every part of the rim, the accumulating ejectamenta will roll or slide down under the influence of gravity and inter-friction until a state of equilibrium is reached, with its corresponding angle of inclination. Inner and outer-slope will thus be identical and in keeping with the nature of the ejected material. For strato-volcanoes this angle of slope is *grosso modo* from 30° to 40°, an inclination which is actually preserved along the outer slopes of strato-volcanoes.

In fact, supposing that the accumulation of ejectamenta and the subsequent development of the cone continues in height and corresponding base, it is clear that such may continue normally as indicated above, until its basis reaches the rim of the eruption-point a—a' (in section a—b'' and a'—b'''). Should the accumulation continue after this moment, then a new phase will have been inaugurated, as a normal readjustment of the ejected material rolling down towards the eruption channel *a—a'* will be hampered by the pressure of the outflowing, débris-charged gas-current; whilst that rolling down along the outer slope, *tc—t'c'*, of the cone will not be subjected to such a resistance. The former will consequently be dammed up. Hence the greater thickness of the accumulated débris-strata on the cone-pipe side, as LINCK had already demonstrated experimentally. Hence, again, the lesser inclination of the cone's apex towards the cone pipe as against the outer slope.

Considering now that a volcanic cone-pipe has been built up under the influence of the factors sketched above and that the gas-current extruding from the conduit, *p*, will be vertically directed, this direction being that of least resistance, it is clear why the encompassing wall of cone-pipes will always tend genetically towards the vertical. (Chaine des Puys, Auvergne, Vesuvius, Slamat etc.). This feature is, in other words, a causal effect of the mode of formation of volcanic cone-pipes. Whereas this feature is genetically inherent in no other part of a volcanic structure but its cone-pipe; and whereas the universality of its occurrence with calderas distinctly shows that this feature is a genetic quality of these structures also, the conclusion would seem justified that the vertical encompassing wall of calderas constitutes the wall (or its remnant) of the *then* volcanic pipe. In other words, *that the caldera-capacity represents in dimension and shape, the size and form of the magmatic conduits concerned and their respective extensions, the cone-pipes, of the then volcano or volcanoes.*

Before investigating whether this preliminary conclusion finds additional support from other equally well established phenomena, we will first study more closely this vertical encompassing wall of cone-pipes.

ESCHER's remarkable experiments (4) (Pl. 7) demonstrated the mode of development of such a channel in a homogeneous cover when pierced by a vertically directed gas-current. It is true that a volcanic cone does not represent the body of a pre-existent mass which covered the eruption-point and that strictly speaking, the cone-pipe is not as a rule pierced through a pre-existent cone; on the contrary the latter is built up all round the former. ESCHER's basis would consequently seem to be false. Yet in considering the mode of formation of volcanic cones as detailed above, it is clear that in its results there is no difference between the piercing of a pre-existent complex of strata by a gas-current and the keeping open of a channel by a débris-laden gas-current which would be covered by the ejected material but for the clearing action of the current. (The cone-pipe walls of lava-volcanoes *(Schildvulkane)* encompassed by more homogeneous material, yet formed in an identical way, are also vertical (5) p. 454 ff.).

If however the complex of strata through which such a gas-current is extruding should be heterogeneous, i.e. constituted of irregularly alternating more and less resistant strata (Kimberley pipes), then cavities may actually be hollowed out in the *grosso modo* vertical wall of an eruption channel (conduit or/and cone-pipe) by the greater eroding effect of the action of the current on strata of less resistance; which is clearly demonstrated in ESCHER's experiments (4) p. 70—71. Yet it should be noted that such deflections from the normal will only occur, theoretically, subsequent to much heavier explosions (gas-extrusions) than those which caused the erection of the cone-pipe. In every other case, in fact, the erosive effect of the ejectamenta-laden gas current, if any, may be neglected, as the material constituting the con-pipe arrived *in situ* at its state of equilibrium under the influence of gravity *and* that of the pressure of the gas-current. Now, as the former remains unchanged, it is clear that the state of equilibrium will remain unaffected also, unless the latter (gas-pressure) is considerably augmented (a considerable diminution of the gas-pressure may cause a local down-fall of material, as we shall see). Finally we would draw particular attention to a very remarkable observation made by PERRET (3) (p. 113) to the effect that a magma rising in a cone-pipe will tend to fill up any such deviations from the vertical in the wall of the cone-pipe by a process which PERRET describes as "plastic lining". Schematically we could represent the vertical section of a cone-pipe with its orifice, the crater, *during* a constant ejectamenta-charged eruption as given in Fig. 2. At the close of such an eruption the ejectamenta accumulated all round the crater will be in a state of labile equilibrium which may be disturbed by the slightest shock, an air-vibration even, as PERRET was able to establish. Thus the enormous quantities of latent energy accumulated in the masses surrounding the orifice, the crater, when rendered kinetic, will tend to establish a state of equilibrium, thereby sometimes causing huge avalanches to crash down to the bottom of the cone-pipe, and thus enlarging the *crater* and steepening its inwardly directed slope, to an angle greater than that corresponding with the angle of the slope of a normal débris-cone of the material converned, an angle which is preserved in that of the outer slope of a volcanic cone (3) (p. 99 ff and Fig. 63, p. 103).

Before closing our study of the eruption-channel, i.e. that of the magmatic conduit and its extension, the cone-pipe, we will point out that its mode of formation will tend to produce at least three principal zones of less resistance, to wit: one situated more or less centrally at or near the vertical axis of the eruption-channel; a second along the border of the said channel, which we will call the inner-peripherical zone; and a third more excentric still, which we will call the outer-peripherical zone. The existence of these zones is strikingly manifested in nature by the common occurrence of more recent points of eruption situated peripherically as well as centrally with respect to older channels (3) (p. 19, Fig. 3; (7) Kawah Ratoe of Tangkubang Prahoe; G. Tjiremai, a.o.). The phenomenon is also manifested by a marked tendency of primary fumaroles to occur centrally or else inner- or outer-peripherically and which is beautifully illustrated in the structure of the G. Pajang (Batoer-Complex), the remains of which disclose fine sections, vertical and horizontal. KEMMERLING established that within the, *grosso modo*, vertical cone-pipe, the solid central core is separated from its clastic mantle, the cone, by a zone of breccias enclosing the said solid core.

This remarkable phenomenon of the re-occurrence of younger eruption-points, centrally or/and peripherically situated in relation to an older one, which is as general an occurrence with volcanic cone-pipes as with calderas, strikingly discloses yet another close similarity between these two phenomena. A few examples, which may be multiplied ad libitum, of peripherically situated younger eruption-points of calderas are the Fogo Island, G. Batoer (with its G. Abang), the Knebel-caldera (Rudolf-crater and the S. E.-craters), the Piton de la Fournaise (Reunion) (9) (p. 263) with its peripherically arranged fumaroles; whilst more centrally situated younger eruption-points are exemplified in Fogo-Island (10) (p. 29, Fig. 32), Barren Island (11), G. Batoer (the active cone), Vesuvius, etc. etc.

Moreover we find both types abundantly represented among the lunar calderas.

On caldera-capacities considered as the original openings of older volcanic cone-pipes.

Having indicated the similarities between calderas and volcanic cone-pipes and having shown that at least one of the qualities they possess in common, that of the vertical inner wall, is a genetic feature of the latter and most probably also of the former, we will now examine:

1. How, if at all the genesis of calderas could be explained rationally on the basis of the assumption that the phenomenon differs from that of a volcanic cone-pipe in relative size alone;
2. Whether examples of caldera-formation in the manner assumed by us are known; and
3. Whether and how the actual remains of caldera-structures furnish a rational basis for reconstructing their history and mode of development.

Sub. 1. *Simple Calderas.* If the conception of the word *caldera* includes all those "depressions" of volcanic origin which are enclosed in toto or partly by a cone-shaped débris-mantle characterized by a steep, semi-vertical or vertical inner wall and a normal inclination of its outer slope, then the word would also include those volcanic "depressions" within which no younger eruption-point could be established. We shall call this kind of calderas *simple calderas*, the type of which is represented by, for instance, the Ngorongoro-caldera in East Africa, with a diameter of 17 to 22 km (personal communication of H. RECK), the Askja, of some 9 by 9.5 km [1]) and the Knebel-caldera (Island) of some 4.5 by 2.5 km in diameter.

Now, whereas the diameters of eruption-channels and their corresponding cone-pipes may vary from a few meters and even less (adventive craters, hornitos etc.) to 200 m (Vesuvius before 1906) (3), 400 m and 500 m

[1]) These dimensions, derived from his topographical map, do not seem to agree with H. RECK's estimates of its size, which he takes to be about 55 km^2 (p. 45).

(Vesuvius after 1906), 5.6 km (Kilauea) (5) (M. Loa, etc.), it seems extremely difficult to understand why the conception should be inadmissible, that the diameters of cone-pipes have been larger in the past than the average of those we know now, and, consequently, why the calderas above mentioned could not be the remnants of the cone-pipes of volcanoes. On the contrary, the very absence of smaller eruption-points within such calderas, although it could never be invoked as a direct proof, may plausibly be explained by such a conception, which would readily solve a haunting enigma.

In the case of the Askja-caldera, moreover, the above conclusion is strengthened by the structure and nature of the encompassing wall, the Dyngjufjöll, more especially by the typical peripherical arrangement of the smaller calderas, the so called "Lava Plateau", in the north east, and the Knebel-caldera in the south east of Askja, and again by a repetition of this mode of occurrence of younger eruptive channels round the periphery of the Knebel-caldera. In fact here we find the Rudolf-crater, the south eastern craters and southern fumaroles grouped in a way precisely similar again to that of secondary cones round older volcanic vents (see below) (6) (12).

THORODDSEN (12) (p. 198) considers rightly, in our opinion, the Dyngjufjöll as a remnant of an ancient strato-volcano. This view of the nature of the Dyngjufjöll finds support in its structure of alternating strata of lavas and clastic material and in their directions of slope ; yet, that the enclosed Askja-caldera would have been produced subsequently, and by down-throws of part of the upper structure along vertical fault-planes, we cannot admit.

Sub. 2. *Composite calderas.* Under this head we comprise such calderas as have or have had one or more indubitable eruption-points, situated more or less centrally or peripherically to the encompassing wall (the inner wall). (Barren Isl., Tenger, Vesuvius, etc.). This definition would virtually comprise also forms of calderas with eruption-points so excentrally situated that they actually occupy an outer-peripherical position. Such is the case e.g., as we previously pointed out, in the Askja- and Knebel-calderas which we discussed sub. 1 as *simple calderas.*

Now, if we admit that the caldera-space constitutes the space within the remnants of the cone-pipe of an older volcano, it implies that the composite-calderas would have been formed by a *process of filling up,* to a more or less degree, of such older cone-pipes by the products ejected by one or more succeeding younger eruptive cones.

The exact conception of the mechanism of such a process may best be realized by a description of such a caldera-formation which was actually witnessed and minutely registered in all its phases of development. It shall at the same time be an answer to the question posed sub. 2.

The example we shall choose is that of Vesuvius, which, with its Somma encompassing a still active eruption-point, represents the classical example of a composite-caldera. We choose this particular example because we know of no other strato-volcano, whose history has been so accurately registered during such a long period as has that of Vesuvius. Among the records we would specially mention those of the observations made by PERRET (3) of the eruptions of 1906 and 1913—'20. Their accuracy, minuteness and instructiveness and the vividness of their description permit one to follow the development of the phenomenon step by step and support, while severely testing, our contentions.

First of all we wish to place on record that both MERCALLI and PERRET (l.c. p. 14) seem convinced that the encompassing Somma-wall is nothing but the inner wall of the older Somma-volcano. DANA arrived at a similar conclusion with regard to the inner wall of the Kilauea-caldera [1]). Yet, so far as I know, neither of them nor any one since seems to have realized that these conclusions with respect to the caldera-walls of Kilauea and Vesuvius might contain the solution of the caldera-problem in general. Let us now study the history of the present eruptive channel of Vesuvius from the time immediately preceding its eruption of 1906.

The crater, which is the *orifice* of the cone-pipe, situated a little excentrally within the encircling Somma-wall, was then some 180 m in diameter, while that of the Somma-caldera measured some 3.5 km.

When we consider the observed phenomena bearing more specially on our subject, we find that the diameters of the crater and of the cone-pipe were enlarged respectively to 1000 m and 400 m by the 1906 eruption.

The passage from the lower-rim of the *crater* to the top of the cone-pipe-wall was sharp, not gradual (l.c. p. 98) ; the inclination of the crater was 45° and that of the cone-pipe consequently steeper ; the depth, from the top of the cone to the floor or the crater, measured 400 m so that the height of the steeper cone-pipe-wall above the crater-floor must have been some 100 m. These data characterize conditions actually existing in 1909, i.e. after three years of denudating activity. That the cone-pipe wall was perpendicular or nearly so, during and even years after the 1906 eruption, is testified by the various photos (3), and still more conclusively by the shape of the gas-column, 13 km in height, which was ejected through the cone-pipe during the eruption. In fact the apex of this inverted cone barely measured 20° so that its conduit must have had an inclination of at

[1]) In view of the greatness of the discharge in 1823, — so undermining, owing to its extent, as to drop abruptly to a depth of some hundreds of feet the floor of the crater leaving only a narrow shelf along the sides, — we reasonably conclude that at that time the lava-column beneath the floor was of as large area as the Kilauea pit itself, — or nearly seven and a half miles in circuit. We may also infer that, immediately before the discharge, wherever there was a lava-lake, the liquid top of the column was up to the floor of the crater, and elsewhere not far below it.... When the floor of the pit fell at the discharge in 1840 it was not thrown into hills and ridges, as it might have been had it dropped down its four hundred feet to solid rock in consequence of a lateral discharge of the lava beneath; on the contrary it kept its flat surface, thus showing that it probably followed down a liquid mass, that of the subsiding column of lava. (13) pp. 151—152.

least 80°. This phenomenon therefore furnishes a striking corroboration of our theoretical deductions from a study of the mechanism of cone-pipe-building which led us to the conclusion that the walls of volcanic cone-pipes will causally tend towards the vertical. In fact these extremely pointed inverted gas-cones, far from being an accidental mode of occurrence of this or previous Vesuvius-eruptions, are characteristic, as is well known, of certain types of gas-eruptions known as volcanian eruptions. This kind of eruptive manifestation, moreover, does not pertain to any specific type of volcano but may and often will occur in the course of any period of activity of any volcano.

PERRET does not describe the condition of the crater-floor immediately after the eruption of 1906 ; three years later, however, it appears that on it several débris-cones, derived from avalanches of crater- and cone-pipe-material, had accumulated against the steep wall of the cone-pipe. This condition remained practically unchanged until 1913. A new phase then announced its approach by an intensified activity of the magma.

Subsidences and magmatic absorption of parts of the crater floor and in particular of the foot of a débris-cone, and alternating formation and subsidence of eruptive conelets were the external signs of an incandescent magma rising in the conduit, the typical glare of its liquid surface manifesting itself on July 8 [1]).

It should be remembered that a conical depression (100 m in diameter and 20 m deep) with a semi-vertical wall was consequently formed in the foot of a (the south-western) débris-cone by subsidence. From its centre a volcanic conelet built itself up, its base closing over the lower part of the said depression. At the end of October lava began to flow out from the top of the conelet, gradually filling up first the enclosing depression and then the entire cone-pipe up to its junction with the lower rim of the crater.

"The rising lava soon formed an eruptive conelet, and from this time "onward, up to the day of writing (1921), the entire course of events in "the external activity of this volcano has been characterized by an almost "continuous process of crater-filling activity (Fig. 61, our Fig. 3), through "superposition of material erupted explosively and effusively from the "eruptive conelet and adventitious vents."

Thus PERRET *(l.c. p. 119 ff.) summarizes his exact observations of a most remarkable phenomenon by the development of which the cone-pipe of Vesuvius of 1906 was converted into a miniature caldera, that of 1921, by a filling-up process identical, no doubt, with that which at one time (An. 79 b. C.?) converted the older Somma-pipe into the caldera-wall of the younger Vesuvius of that time.*

All the typical features characterizing terrestrial calderas equally

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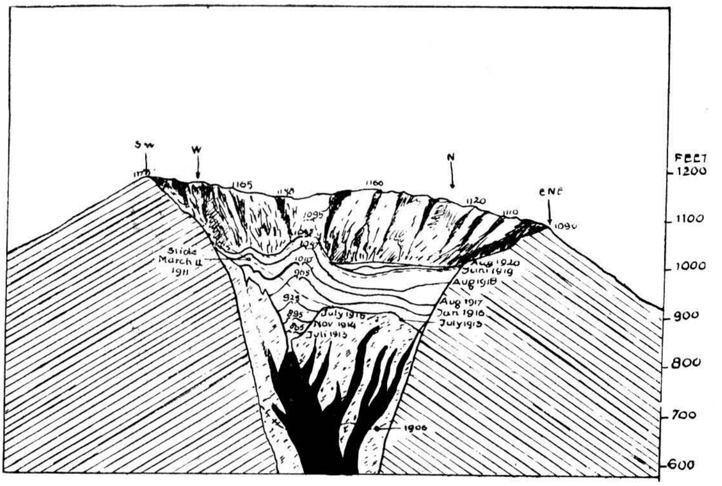
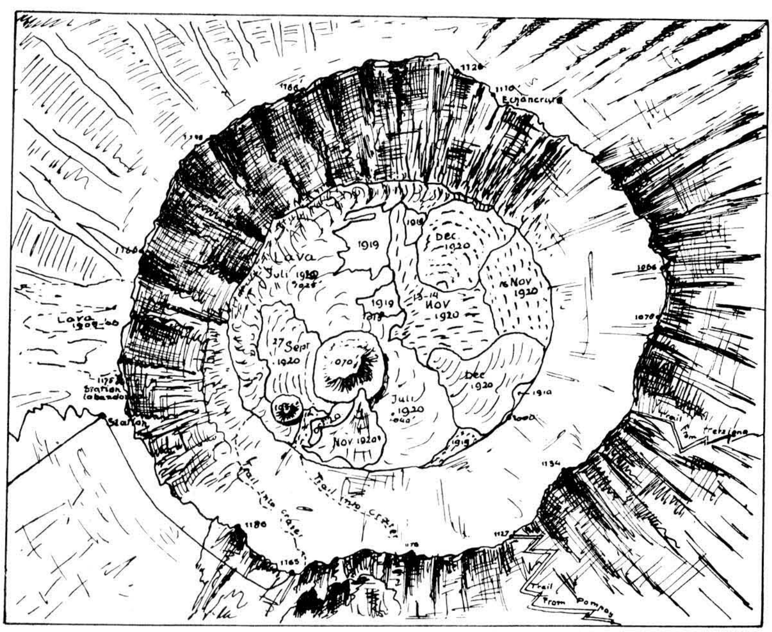
[1]) The records of the very accurate observations during the entire course of development of this phenomenon place it beyond any doubt that the ascent in the cone-pipe of the incandescent lava (magma) with its highly corrosive vapours and gasses occurred excentrally (semi-peripherically).

characterize the actual minute younger Vesuvius caldera ; the abnormal proportions between the diameters of the younger eruption-channel and of



DRAWING BY MALLADRA.

Fig. 3. Schematical representation of the growth of the eruptive conelet and the resulting process of filling up the crater of Vesuvius. Composite caldera-formation. Drawing by Malladra; copied from (3) Fig. 61; section of Fig. 4.



FROM MALLADRA. MAP OF CRATER FLOOR ON DECEMBER 31, 1920.

Fig. 4. From Malladra. Map of crater floor of Vesuvius on December 31, 1920, showing a perfect composite caldera of fair size. Copy (3) Fig. 62.

its caldera are of an order identical with other, larger terrestrial composite calderas ; the *grosso modo* vertical encompassing wall is present also, even though it is now almost entirely hidden from view by the filling ; the flat bottom, generally speaking, was caused and maintained by the extrusion of highly liquid lava ; finally, if the lava extrusions had been succeeded here by ejection of loose material (ashes, lapilli, etc.), the characteristic "sandsea" of Dutch East Indian and other volcanoes would certainly have been present in this case also. Thus this "sandsea"-phenomenon would likewise have found a ready explanation.

It is now necessary to test our contention, that the caldera space is nothing but a remnant of partly filled up older cone-pipes, on some other well known calderas.

On the probable mode of formation of certain calderas.

If the younger eruption-channel of Vesuvius had extruded centrally in the resent Vesuvius-caldera above described, just as it occurred in the G. Raoeng (7) (p. 58, Phot. 18), then we should have had a form of caldera comparable in every respect with that of Barren-Island and similar calderas.

The crater of the Slamat (7) (p. 35 ff and Phot. 8) presents a more composite caldera. "The crater proper (diameter over 400 m depth 228 m) is situated in the south western part of the cone and is enclosed on its north eastern side by some three crater-rims. Between the most northern and the central one a great plane or sandsea spreads out, strewn over with numerous bombs" (l.c. p. 38). Evidently we have here three inter-telescoping cone-pipes mutually tangent in the south west, the older ones of which are enclosing their successors (l.c. p. 39) in consequence of a successive displacement of eruption-channels in a south western direction. The result of such an occurrence was that the cones of the younger eruption-points could only develop individually in a north eastern direction and hence it is only in that direction that we find their remnants, namely the individualized encompassing walls and the sandsea (Fig. 5).

To nobody, we are sure, would the idea occur that the walls of this caldera, though a miniature of its kind, might be the product of down-throw, subsidence or magmatic fusion. Nobody could doubt that these walls are the remnants of older cone-pipes of which only the oldest was levelled a little or hollowed out, probably by the erosive and denudating action of (a) gas current(s). Yet, apart from its total size, this kind of caldera differs from the occurrences generally designated by that name, only in so far as the diameters of the older and younger cone-pipes differ but little here, which implies that the free development of the more recent was hampered. Still in essentials there is no difference whatever between this and other calderas.

The crater of the Sendoro (7) (p. 44 and Photos 10 and 11) presents a similar caldera within which "the remains of a younger cone encompassed by an older wall" is visible so that this crater again reproduces the live type of caldera with all the characteristic features.

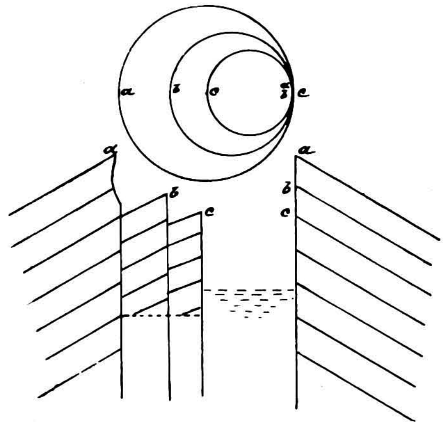


Fig. 5. Schematical section of the Slamat cone-pipe and crater shewing its caldera structure. Compiled by me after the description and aeroplane photos from (7)*pp* 35*ff* and Photos 8—9). *aa* = section of oldest cone-pipe; *bb* and *cc* of younger pipes with sandsea between *a* and *c* on the left.

It would not be difficult to give any number of other examples of typical caldera-craters (or crater-calderas) and it was in fact the comparative study of crater-types, especially the East Indian, and calderas, which led us to the conviction that these phenomena are essentially alike and differ only in the relative size of the eruptive channels.

Let us, finally, study the mighty caldera of the Batoer-complex, the Molengraaff-caldera on Bali, with its axes measuring 13.5 km in a N.W.—S.E. and 10 km in a S.W.—N.E. direction (8). Its floor lies at an altitude of 1000 m the highest points of its rim at 1745 and 2152 m and the lowest at 1267 and 1336 m respectively. Fig. 6, compiled after a topographical sketch by KEMMERLING, supplemented by my own observations, gives the main features of the caldera, a section of which is also given by KEMMERLING (8) [1]).

The vertical inner wall of this, the Molengraaff-caldera is very remarkable indeed. It closely follows the rim of the caldera between the points 1745 (G. Penoelisan), 1371 (W. side), 2152 (G. Abang), and 1270 except where it is interrupted by downfalls or hidden from view by débris-material, as is specially the case, e.g. E.-S.E. and N.-N.W. from the point 1371. Within this huge enclosure, which we will henceforth call the

[1]) This section is for its north western part incorrect, in so far as it does not show the vertical wall of the Molengraaff-caldera there, although parts of it may still be recognized here and there between the points 1745 and 1371, however much destroyed it be by avalanches. The vertical inner border of the lower plateau, at the south east side of the section, is most probably a remnant of the wall of the Molengraaff-caldera (the "outer-wall"), and KEMMERLING seems to concur with this interpretation of the nature of this feature (l.c. p. 61).

outer wall, in contradistinction to another, powerful yet smaller caldera-wall enclosed by it, we find the remnants of the latter, as another vertical,

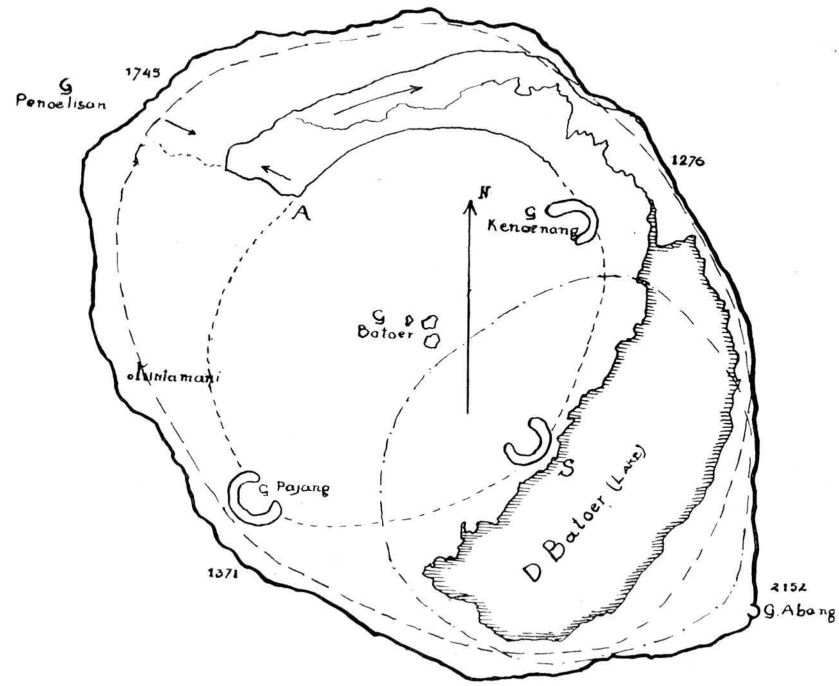


Fig. 6. Main lines of the Batoer-complex with its Molengraaff-caldera; after a topographical sketch (8) and personal observations.

roundish caldera-wall, the diameter of which must have measured some 7.5 km From a point A. marked on the sketch, eastward to a point close to G. Kenoenang, this steep *inner wall*, towering up vertically to a height varying between 200 and 300 m above the floor of the caldera, is scarcely modified. Its extension in the opposite direction, towards G. Pajang, is very mutilated and in parts almost destroyed, whilst that part which probably extended between G. Pajang, the eruption point marked S. and G. Kenoenang, has completely disappeared.

This steepness, *casu quo* verticality, of the inner-walls of the Molengraaff-caldera and its inner caldera, suggest that they probably constitute the remnants of the respective cone-pipes and their conduits.

Moreover, the said plateau, a sand-sea *optima forma*, points in the same direction, as it evidently constitutes a remnant of the cone of the inner caldera.

In fact it slopes outward and the general direction of its incline is towards the E. (vide its drainage) i.e. in exactly the same way as the rim of the Molengraaff-caldera between G. Penoelisan (1745) and the point 1276. Both the direction of these inclines and their parallelism may safely be taken as a result of the influence of current winds on the ejected material during the building processes of the respective cones. On the other hand, it would be inadmissible to interpret this concurrence of inclinations and the outward direction of the slope of the plateau, as the necessary results, i.e. causal effects of subsidence, downthrow, explosion or fusion.

Finally, we find peripherically arranged along the border of the „inner-caldera" first G. Pajang, than probably the eruption-point S. and finally G. Kenoenang, on the very zone which would have marked the zone of least resistance of the "inner volcano", namely on the zone situated between the solid core and its encompassing cone.

Since the erection of the inner-volcano above mentioned, it would seem that another eruptive channel forced its way, destroying or lowering not only the south eastern part of the *inner wall* but blowing away also part of the south eastern wall of the Molengraaff-caldera. Proof of this we find in the remaining half of G. Abang which is outer-peripherically situated in the *outer wall,* and which volcano was most probably halved in precisely the same way as was the *Piek of Rakata,* (on the outer periphery of Krakatau) during the well known Krakatau eruption of 1883.

This complex of Batoer-eruption-channels, localised within the encompassing *outer wall,* would thus have formed a twin-volcano similar to Tangkoeban Prahoe, which latter also must have been enclosed within an encompassing wall (14) (p. 732) the remnants of which may still be traced over a distance of some 15 km from G. Nanggarak (S. of Tjisaroea) over G. Lembang and Pr. Malang as far as Pr. Pangoekoesan (7) (p. 73). The present stage of activity in the history of the Molengraaff-caldera would have been inaugurated, then, by the eruptions of the peripherical eruption-points, G. Pajang, *S,* and G. Kenoenang, and finally by the eruptions of the centrally situated, still active G. Batoer, which is continuing to fill up the Molengraaff-caldera to the present day.

In the foregoing we have demonstrated by a few examples, which could be multiplied *ad libitum,* that the caldera phenomenon in its various aspects may be plausibly explained on the assumption that the vertical wall encompassing the caldera occurrence is nothing but the wall of an older eruption-channel, its cone-pipe or crater, or their remnants. Thus a composite caldera (see above) would be the remnant of an older eruptive channel filled up in part or *in toto* by younger eruption products, emanating from an inner, more or less considerably reduced, younger channel during a period of locally renewed magmatic activity.

The mechanism of such a filling-up process, resulting in the production of a miniature composite caldera, could be followed step by step during the Vesuvius-eruption of 1913—1922 (vide Figs. 3 and 4).

Should this conception of the nature of the caldera-phenomenon be correct, then we would have to conclude e.g. that the intensity of terrestrial volcanism has been dimishing over a large part of our globe at least since Tertiary times and perhaps since an earlier period. Whether such diminution dates from still earlier geological times, whether it comprises terrestrial volcanism in general, whether it is only of a local, relative or/and intermittant character, are questions the answer to which would require more extensive and detailed studies all over our globe.

It is my personal conviction that aeroplane-photography, if appropriately and systematically conducted, may render considerable service towards the solution of these questions and to that of magmatic activity in general. We do not consider it unlikely that in this manner the presence of terrestrial calderas with dimensions equal to or even surpassing those of the moon may be located.

On zones of secondary eruptions and on the causes of displacements (migration) of eruption-channels.

In the foregoing we have already touched upon (p. 185) another phenomenon pertaining to cone-pipes and calderas alike, which, consequently again points to an identity in substance of these volcanic phenomena. Considering moreover the universality of its character and the identical way of its mode of occurrence in the case of both cone-pipes and calderas, it constitutes a strong indication that the phenomenon may be a genetical feature, inherent in the formation of these volcanic structures.

We are alluding to the marked tendency of secondary eruption-channels to occur e.g. on the periphery of older eruption-channels. This phenomenon occurring universally, as is well known, in all kind of volcanoes (Hawaian volcanoes, Vesuvius, Bromo-Segoro-complex etc. etc.), pertains equally to calderas (Molengraaff-caldera, Fogo Island, Vesuvius-Somma-complex Askja-Knebel-group, etc. etc.).

Although secondary (i.e. younger) eruption-points may occur also in other places and from other causes, we will restrict ourselves here to the study of this particular mode of occurrence.

The occurrence of secondary eruption-points has hitherto been currently, explained, as a causal expression of the influence of fissures or faults radially or periclinally directed, whilst, inversely, the presence and *quasi* mode of occurrence of these secondary eruption-points is often advanced as the only vindication of the assumed existence of such fissures and faults (14) (7) (3) (5, p. 415, etc.). We do not wish to deny that eruptive occurrences may have been provoked by the presence of fissures and faults ; yet the idea, that the latter constitute the main (only ?) and primary cause of the former, we cannot admit unreservedly.

In fact, when considering the mode of arrangement of these secondary eruption-points with respect to the crater or caldera concerned, it soon becomes obvious that we may distinguish three main groups, i.e. : 1. That in which they are more or less centrally situated ; 2. that in which they are arranged along the inner side of the craters or calderas (inner-peripherical); 3. that in which they are arranged on or outside the cone-rim of craters or calderas (outer-peripherical).

The natural section of G. Pajang shows that the magmatic core, the filling of the cone-pipe, is separated from its clastic cone by a zone of breccias. PERRET (3) observed a similar occurrence at Vesuvius, a form of which he designated as the "plastic lining" of the cone-pipe wall. Which ever form the phenomenon may effect it may reasonably be expected that the cooling effect of the wall on a lava-column rising in its conduit (or cone-pipe) will tend to cause a zone of discontinuity between such column and its encompassing wall and that such tendency will be accentuated by the shrinking of the lava subsequent to its consolidation. Its formation is consequently genetically inherent in the mode of formation of a volcanic cone. (N. J. M. Taverne arrived at a similar conclusion in 1925).

The problem of the occurrence — so frequent — of secondary eruption-points and fumaroles arranged inner-peripherically, would thus find a ready solution in the presence of this zone. Moreover it would explain the peculiar and marked tendency of more recent eruptive and fumarolic action to (inner-) peripherical migrations, a phenomenon which is so common in all volcanic massives (see Fig. 7).

How are we to explain, however, a similar tendency of magmatic activity

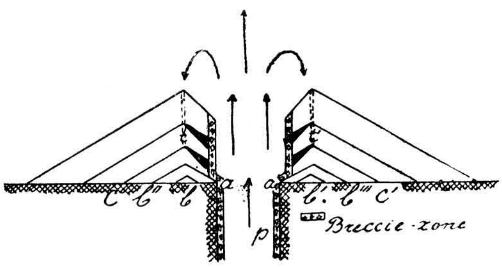


Fig. 7. Schematical vertical section of a volcanic cone shewing that the tendency of younger eruption-points (fumaroles etc.) to peripherical migration is a genetic quality, causally inherent in the mode of formation and subsequent structures of volcanic cones.

to that super-excentrical displacement of its successive sites which we have qualified as outer-peripherical?

When studying the structure of a volcanic cone more closely, we find that the zone of less resistance above described is bordered along its outer periphery by the clastic cone which, from this zone outwards, *is built up in anticlinal fashion.*

It is clear that the highly tensioned magmatic gasses and vapours, highly corrosive at that, will tend to discharge along this zone of less resistance and thus to penetrate into these clastic anticlinals, the roots of which are open along the said zone. Arrived at the tops *t*, *t'*, etc. of these anticlinals (which are again arranged, *grosso modo*, along a vertical concentric plane going through the top-rim) these vapours will meet with an extra-resistance when arriving up against the downward flank of the anticlinal. They will consequently collect at these several tops and their tension and corrosive capacity will tend to make them drill their way vertically through the covering masses, causing their discharge at last along and beyond the top-rim of the volcanic cone, i.e. *outer-peripherically*.

It is evident, therefore, that the outer-peripherical arrangement of secondary eruption-points and fumaroles, which pertains inherently to calderas and smaller volcanic cone-structures alike may be readily explained from the mode of formation of a volcanic cone surrounding its cone-pipe.

A striking confirmation of our contention as to the identity of cone-pipes and encompassing caldera-walls is again furnished by the Batoer-complex. A close study of the section of this caldera (8) discloses in its S.E. corner a remnant of a vertical inner wall, which is the inner border of a remarkable plateau situated at the foot of the bisected cone of G. Abang, and which in its turn constitutes part of the *outer wall*, i.e. of the Molengraaff caldera-wall.

In respect to this main-wall of the great Batoer-caldera, the bisected eruption channel of G. Abang [1]) is situated outer-peripherically whilst the plateau extends between a remnant of the original encompassing wall of the said Molengraaff-caldera and the bisected eruption channel. Hence we find that the slopes of the said plateau, which evidently represents a remnant of the old Batoer-cone, are directed inwards *and* outwards in anticlinal fashion.

It would seem that we have now sufficiently explained and founded our contention about the real nature of the caldera phenomenon, to which subject we intend to return shortly in a second communication.

Finally we have to offer our sincere thanks to both Dr. P. TESCH, director of the Geological Survey of the Netherlands at Haarlem, and to Mrs. E. A. VAN OOSTERZEE—BEELAERTS VAN BLOKLAND at the Hague for their kind assistance in the execution of the drawings which accompany the text.

The Hague, September 1927.

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[1]) It would seem that section and description do not correspond completely. The former is in contradiction also with my personel observations. Apart from my rectification in the foregoing regarding the interpretation of the north western and western wall of the Molengraaff-caldera, it should be noted that the wall below the top of G. Abang is very nearly vertical. This fact seems to find confirmation in KEMMERLING's own descriptions appearing on pp. 51 and 61 of (8).

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