

NEW DATA ON VOLCANIC GASES: THE 1938 ERUPTION OF NYAMLAGIRA.

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ABSTRACT. On January 28, 1938, an eruption broke out at Nyamlagira, an active volcano in the Virunga Range, north of Lake Kivu (Western Rift Valley, Africa). The activity that existed in the crater and which included numerous small lava lakes of Hawaiian type shifted to a place called Tshambene, at the southwestern foot of the mountain. The eruption has lasted for more than a year, and at this time (June, 1939) there are no signs yet that it may stop. A summary of events up to October, 1938, is given, together with the results of temperature measurements, spectrographic analyses of the flames, and estimates of the gas discharge. The amount of gases discharged is very low compared to the amount of lava. The rôle of gases in eruptions of this type may be less than is usually believed. A detailed report is forthcoming.

EARLY in February, 1938, news came through that an eruption had started at volcano Nyamlagira (also known as Nyamuragira) in the Albert National Park, Kivu Province, Belgian Congo. The University of Brussels (Cassel Fund) decided to have a study made of this eruption, and coöperation was established to this effect with the "Institut des Parcs Nationaux du Congo Belge." The writer left Brussels by plane a few days later. When he reached the volcano on February 28, the eruption had already lasted for a month. He arranged to remain permanently on the volcano until September, when he was called back to Europe. The eruption was still going on at that time, and reports received since indicate that it may last a few months more. The volume of lava erupted up to now (June, 1939) runs over one billion cubic meters; this eruption of Nyamlagira is thus one of the few large eruptions ever witnessed by man.

Nyamlagira is one of the two active volcanoes in the Virunga group, north of Lake Kivu, in the Western Rift Valley. This volcanic chain has become known mainly through the work of A. D. Combe,¹ of the Geological Survey of Uganda, who has studied with great care that part of the volcanic field that lies within British territory and is known as the Bufumbira area. The eight main volcanoes of this chain stretch across the floor of the Rift Valley in an East-West direction, approxi-

¹ Combe, A. D., and Simmons, W. C.: The Volcanic Area of Bufumbira, South West Uganda. Geol. Surv. Uganda Mem. III, Part I. 1933.

mately 1°30' south of the Equator. The lavas of the westernmost volcanoes abut against the western wall of the valley, whereas the eastern volcanoes, which form the boundary between Uganda and the Belgian Congo, lie in a deep bay (Bufumbira Bay) carved by tectonic processes in the eastern margin of the Rift Valley. The piling-up of these eight big volcanoes across the floor of the depression resulted in its damming, the formation of Lake Kivu, and a reversal of drainage in parts of the area.

The oldest volcanoes of the chain are probably not older than Pliocene. The two westernmost volcanoes, Nyamlagira and Niragongo,² are still active.

In spite of the fact that all the historically-known eruptions in this area have taken place from the two western volcanoes or from surrounding vents, there is no evidence that the activity migrated as a whole from east to west. Muhavura, the easternmost volcano, bears evidence of very recent activity. Its lavas, according to Combe,¹ are indistinguishable in the field from those of Nyamlagira, and it is surprising that these two volcanoes should assume, in spite of a great chemical similarity of their lavas, such different shapes, Muhavura being a perfect cone 4300 meters high, whereas Nyamlagira (3000 m.) is a shield volcano of truly Hawaiian style. The morphological differences between these two volcanoes are tentatively ascribed to differences of age, Muhavura being perhaps in a later stage of evolution than Nyamlagira.

Very little is known of the activity of Niragongo. Observations at the crater are a matter of chance, as it is usually filled with dense clouds of smoke, impervious to infra-red photography. The glow at night indicates the presence of live lava in the crater. The activity is probably not purely Strombolian, as loud reports are not heard; but there may exist a lava lake of Hawaiian type.

The best descriptions of Nyamlagira in recent times are those by Willis,³ Bowen,⁴ and Combe,⁵ who visited the volcano together in 1929. Since then many changes had occurred and

² Also known as "Ninagongo" or "Tshanina-Gongo."

³ Willis, Bailey: *East African Plateaus and Rift Valleys*. Carnegie Inst. Washington Publ. 470, 1936.

⁴ Bowen, N. L.: *Central African Volcanoes in 1929*. Trans. Am. Geophysical Union, pp. 301-3, 1930.

⁵ Combe, A. D.: *Op. cit.*

the nested sinks that existed then had completely disappeared by the end of 1937, having become successively filled with lava. Just before the 1938 eruption, the crater consisted of a caldera 2 kilometers wide surrounded by a wall less than 100 meters high and breached on the northwestern side by a gap very similar to the gap which, at Kilauea, leads from the floor of the crater into the Kau desert. Lava was quietly overflowing from several pools segregated in an "active area" in the central part of the crater, spreading out on its floor and, through the gap, on the northwestern slopes of the volcano.

On January 28, 1938, in the morning, the active area and the pools collapsed several hundred meters into a deep cylindrical pit very much like Halemaumau. The walls of this pit, made of layers of lava, were covered in parts by an upholstery of fresh lava, indicating that the pit probably served as a channel from which the pools were fed. A few hours later, a number of large fissures opened in the southeastern and southwestern flanks of the mountain and a flood of fresh lava poured out, rushing down the slopes at a tremendous speed. The lava was flowing faster than the fissures could open, so that a few meters below the place on the fissure from which the lava sprang out, the fresh lava flows were cut by the fissures themselves (Plate I, Fig. 2). Drained laterally through these fissures, the crater collapsed and a new sink of colossal proportions was formed within the caldera.

About half an hour after the fissures had begun to open, an explosion occurred on the southwestern flank of the volcano, about 4 km. from, and 700 meters below, the rim of the crater. Apparently a great deal of faulting took place at that time, and several horsts of stratified lava and tuffs were pushed up as blocks 20 or 25 meters high. Spatter cones were born, and a stream of lava began to flow down steadily into the plains at the foot of the volcano. The source of this stream was in a reëntrant angle between the walls of two upthrust blocks (Plate I, Fig. 3).

The events of the first day of the eruption were reconstructed partly from field evidence and partly from the testimony of a witness, the Conservator of the Albert National Park, who happened to be standing on the rim of the crater at the beginning of the eruption. His report, and observations made by him during the years 1931 to 1938, are being published presently elsewhere.

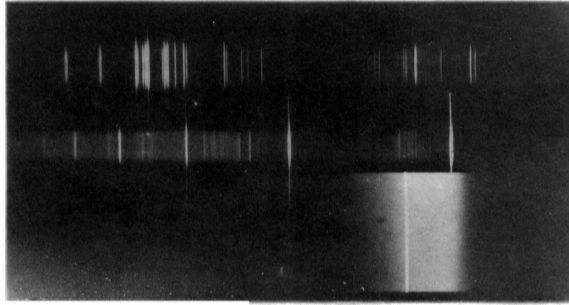


Fig. 1.



Fig. 2.

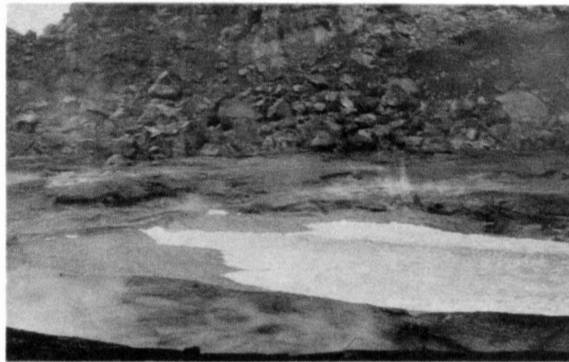


Fig. 3.

Fig. 1. From top to bottom: Argon, hydrogen and flame spectra, in the visible range (3800-7000 \AA). The brighter lines of the hydrogen spectrum are, from right to left, the 6562, 4861, 4340, and 4101 lines of the Balmer series.

The bright line in the flame spectrum is the sodium D line. The bands to the right and left are the $\Delta v=3$ and $\Delta v=4$ groups of the first positive system of N_2 . Three very weak bands are faintly visible at 4360, 4430, and 4440 (slightly to the right and below the 4340 line of the hydrogen spectrum). These bands are unidentified as yet.

Ilford Panchromatic Plate. Exposure: 1 hour 30.

Fig. 2. Nyamlagira, from the southeast. The lighter patches are the flows that poured out on January 28, 1938. A fissure is clearly seen extending through one of the flows and running up to the crater.

Fig. 3. The source of the lava stream at Tshambene. Note the dearth of gases. In the background, an upthrust block (horst). Approximate discharge of the stream: 60 million cubic meters per month.

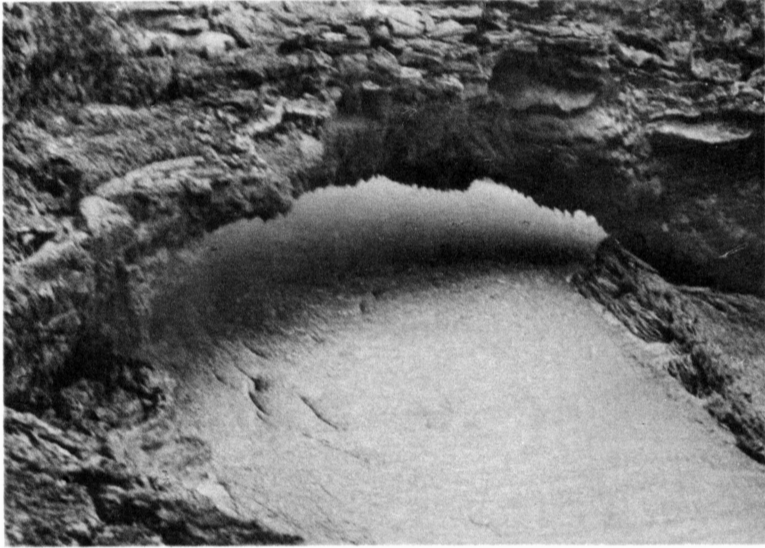


Fig. 1.

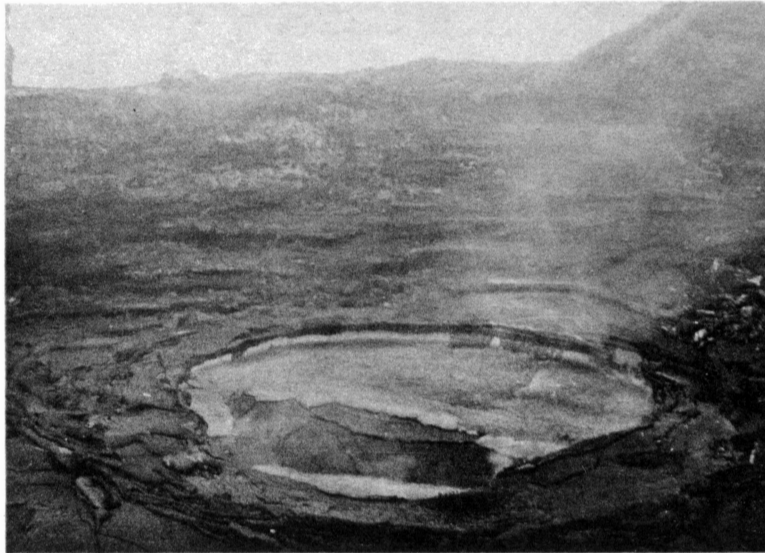


Fig. 2.

Fig. 1. Lava entering the lava lake. The feeder is seen to extend backwards for several meters.

Fig. 2. A lava pool at Tshambene, at the end of a cycle. The level of the lava has fallen half a meter. Large patches of floating crust are being carried away.

At the time the present writer reached the volcano, the main crater of the volcano was completely inactive, except for occasional avalanches in the pit and a row of solfataric vents which had been active for years and never discontinued their activity in spite of the drastic changes that had occurred less than 500 meters from them. Heavy clouds of smoke, loud reports, and a brilliant glow at night indicated that all the activity had migrated down the slope to the place where the explosion had occurred and which is known to the natives as Tshambene.

Tshambene could be approached quite easily, provided care was taken to keep out of the wind. At the time of the writer's first visit, two cones ("Schweisschlackenkegel") were active, tossing up into the air great lumps of incandescent, pasty lava which would fall flat on the ground as pancakes ("cow-dung" bombs). Each explosion was accompanied by a great outburst of gases which would burn explosively at the mouth of the cone. The flames were invisible by day, but became very conspicuous at night; they would condense a few meters above the mouth of the cone to a brown-blue, heavy smoke with the pungent smell of sulfur dioxide.

Smoke was issuing also from a lava lake nested in a depression between two recent cliffs. The lava lake had an elongated, pear-like shape, about a hundred meters in its longest direction. The lava stream was issuing from the foot of a cliff on the farther side of the upthrust block which formed the western wall of the lake depression. The lava came out of the ground without a bubble or a splash, flowing down steadily as a stream 8 or 10 meters wide, at a speed that varied, according to the slope, from 2 to 4 to 10 meters per second or more (Plate I, Fig. 3).

This stream kept on flowing for months and is still flowing now. A succession of rapid changes in the discharge, floods, and repeated overflows of lava produced a tunnel in which the lava would have become buried and concealed except for a few openings in the roof, which provided ample opportunity to observe the flowing lava.

Cones were usually very short-lived. As a rule they began as a steam vent. The jet of steam, growing thicker and thicker, appeared to bore a hole, and great splashes of lava would agglutinate around it, building up in a few days or a few hours a central chimney. Pumice-like scoria-

ceous fragments would accumulate around the chimney and in this manner a cone 15 or 20 meters high would come into existence. Then the projections of incandescent material would gradually decrease, and eventually only burning gases would escape from the glowing mouth of the cone. Another cone would usually form in line slightly higher up on the slope, and the first cone would gradually die out completely. The writer witnessed the birth of several cones at regular intervals of approximately one month. First symptoms of the birth of a cone would generally appear a few days before or after the full moon.

Later, when a number of cones stood in line, fifty or one hundred meters apart, each cone being slightly higher up on the slope, the supply of lava became exhausted, and the projections of lava and scoriae were too meagre to build up a cone. Gases were then seen to issue from large holes in the ground, 10 meters in diameter, and of unknown depth. These gases would burn explosively at a rate of 30 to 60 explosions per minute, each explosion being followed by a short period of down-suction lasting for a fraction of a second. One of these flaming vents remained active for an unusually long period and unexpectedly failed to die out when a new vent was formed. This new vent, it is true, stood much higher up on the slope and was not in line with the other cones. It remained active, according to reports from July to November 1938, and when it died out, was not replaced.

Occasionally, small flows of sticky pahoehoe lava would ooze out from a cone. This would happen only in the early days of its existence. The amount of lava erupted in this manner was absolutely insignificant when compared to the amount discharged in the stream.

THE LAVA LAKE.

Essential features of lava lakes have been ably described by Perret,⁶ Jaggar, and others, and need not be repeated here. The behavior of the lava lake at Tshambene was identical in many respects to that of Halemaumau. At Tshambene the lava was entering from the south, flowing across the lake without any appreciable loss of gases, and apparently sinking beneath the northern bank at places where escaping gases produced much splashing and stirring of the lava. Both types of

⁶ Perret, F. A.: This Journal, 35, 273, 337, 469, 611, 1913; 36, 475, 1913.

fountains described by Jaggar⁷ were of common occurrence, and Jaggar's penetrating account of their activity might be used here without alteration.

Under favorable conditions the lava entering the lake could be seen to issue from a channel which extended backwards under the bank (Plate II, Fig. 1), indicating that the lake constituted probably but a part, and possibly an unessential one, of the circulatory system. When the level of the lava began to subside, it became apparent that there was no deep conduit from which the gases might rise beneath the places where the gas discharge was greatest and the fountains most common; on the contrary these places turned out to be the shallowest of the lake. Further subsidence and continuous shrinking of the size of the lake resulted in its division into halves, and the direction of circulation in the northern half (northern pool) was momentarily reversed, the lava flowing now southwards across the pool. During this subsidence, the channels from which the pools were fed remained for some time at a constant level, and consequently lava could be seen rushing down a fairly steep slope before entering the pools. Eventually the northern feeder dried up, and one of the pools became totally inactive. Activity was resumed a few days later, the lava entering once more from beneath the southern bank and flowing northwards across the pool.

After the size of both pools had shrunk very much, the circulation of the lava became discontinuous and a new type of activity was observed. The lava in the pool would remain motionless and become covered with a thick, immobile, crust, the only signs of activity being one or two fountains where gases escaped explosively, splashing much spatter but producing apparently little effect on the temperature or viscosity of the lava. Then the crust would be suddenly and violently torn apart; great quantities of gases would escape either quietly or with great agitation, and the level of the lava would drop half a meter or so. The crust would be engulfed or large patches of it would be carried aside under the overhanging banks (Plate II, Fig. 2). After a few minutes calm would be restored, lava would enter the pool from one side, filling it up to either its former level, or to a higher, or to a lower one, crust would form, and the cycle would recommence. The length of this cycle seemed to vary in proportion to the size of the pool and ranged

⁷ Jaggar, T. A.: *id.*, 44, 161-220, 1917.

from 3 to 55 or 60 minutes. The whole process was singularly reminiscent of geyser activity. It is perhaps worth noticing that the gas discharge during the long period of calm, at high and constant level, was probably as large as, or greater than, the discharge during the few minutes or seconds which followed the engulfment of the crust and the rapid dropping of the level.

It is impossible here to give a complete account of the observations that were made and which will be published in a detailed report. A complete discussion of the mechanism of lava lakes would exceed the scope of this paper, and a special contribution on this subject is being prepared. As a whole it might be said the facts observed at Tshambene seem to support Jaggar's views rather than Perret's, particularly regarding the mechanism of fountains. The hypothesis may be considered favorably that the gas discharge from the lake is a consequence, and not a cause, of the circulatory motion of the lava. In the writer's mind there is a distinct possibility that gases might not be essential to the mechanism of lava lakes.

TEMPERATURE MEASUREMENTS.

Temperature measurements were carried out with a Siemens Horlborn-Kurlbaum pyrometer. The principle of this instrument is to compare the brightness of a glowing object, e.g. lava, with that of the filament of a lamp mounted in the image plane of a simple telescope. The brightness of the filament is adjusted to match that of the object, and the current through the lamp is read on a milliammeter. For a given wave-length the brightness of a glowing body is a known function of the absolute temperature; the milliammeter may thus be calibrated directly in degrees of temperature. The instrument is handy, portable, and quite accurate ($\pm 10^\circ$ at 1200° C.). The great advantage of this type of instrument is that it allows the measuring of temperatures in perfectly inaccessible places where it would be utterly impossible to thrust a thermocouple or any other device. Satisfactory results were obtained when measuring temperatures at distances of more than one kilometer.

If it is desired to measure the temperature of an incandescent body with a known absorptivity less than 1, corrections must be applied. A chart is supplied by the makers of the instrument that gives these corrections as a function of the readings

and of the absorptivity. The absorptivity of the lava has been measured in the laboratory and found to be, for a glassy specimen, close to 0.68, and for a slaggy fragment of a bomb, to 0.78. Taking 0.73 as an average, it follows that reading in the range 1000-1100° C. must be corrected by an amount that is approximately $25 \pm 5^\circ$ C.

Temperatures measured by this method are of course always surface temperatures. Measurements at places of greater agitation, where the upper, cooler layer is torn apart, should be expected to give higher values than measurements at places of quiet flow. This fact was beautifully demonstrated by a series of measurements at various places along the lava stream. The lava always appeared to be hotter at places of greatest speed, on the steepest slopes. Temperatures half a kilometer downstream were consistently found to be 20° or 30° higher than temperatures at the source, where the lava flowed very quietly.

The same differences were observed in the lava lake. The temperature at the fountains was occasionally found to be 20° or 30° higher than where the lava flows quietly into the lake. The difference is ascribed entirely to the formation, where the lava is flowing quietly, of a cooler crust which is torn apart at places of greater agitation, allowing readings on the hotter layers immediately beneath. Considerable reheating by the burning gases seems to be completely out of the picture at Tshambene.

A few selected values of the temperature of the lava at various places are given in the appended table. The approximation is $\pm 15^\circ$ C.

A great many more temperature measurements, which will be published in a detailed report, have led to consistent results: the temperature of the lava remains constant within 40° or 50°, whether measured at the source of the stream, where it enters the lake, at fountains, at places of great speed and agitation in the stream, or where tiny tongues of lava ooze out from a cone. The difference between the temperature of the lava where it enters the lake and at the fountains on the far side of the lake is no greater than the difference observed at various places along the stream. The conclusion seems obvious that thermal effects of the burning gases, where they burn, are slight. Differences in temperature between opposite ends of the lake cannot account alone for the circulation in the lake.

The highest temperature recorded during this eruption

Date	Locality	Temperature (° C.)
III/31	Lava stream, at its source	1050
IV/19	Lava stream, at its source	1065 to 1085
	Lava entering the lake	1085
	Lava fountain in the lake	1085
IV/20	Small flow from cone 5	1050 to 1075
V/31	Lava entering the lake	1040 to 1050
	Lava fountain in the lake	1075 to 1095
VI/25	Lava stream near its source, seen through opening 1 in the roof of the tunnel (approximate speed: 4m./sec.)	1040 to 1050
	Lava stream 500 meters downstream, seen through opening 4 in the roof of the tunnel (speed: > 10m./sec.)	1085 to 1090
VIII/3	Lava entering southern pool	1060 to 1085
	Spatter fountain in grotto, southern pool	1080
VIII/29	Lava stream seen through opening 1	1050 to 1065
	Lava stream seen through opening 4	1093
IX/1	Fountain in northern pool	1090
IX/18	Lava entering northern pool at low level	1062 to 1068
	The same, at high level, a few minutes later	1030 to 1050
	Fountain in northern pool	1083
IX/19	Fountain in southern pool	1078
	Lava stream seen through opening 1, looking upstream (speed: 4m./sec.)	1030 to 1040
	The same, looking downstream (speed: 8m./sec.)	1040 to 1050
	Lava stream seen through opening 4 (speed: > 10m./sec.)	1075

(1160° C.) was observed in a small, deep chimney, 50 cm. in diameter, which opened on the side of one of the lava pools after it had built itself up to a sort of cone. Flames were rising steadily from this chimney. At the mouth of the cones or in the gas vents, the temperature rarely exceeded 1080° C. and stood more commonly around 1040° or 1050° C. at the deepest level in the cone that could be seen by an observer, standing at the foot of the cone or on the edge of the gas vent.

The fact that the highest temperatures recorded were not greater than 1160° C. led the writer to suspect that the flames were remarkably cool and probably unable to remelt solid lava. They were apparently unable to remelt the crust that formed on the lake, no matter how long they would be allowed to lick it. At places a few meters from one of the large gas vents, small flames were conveniently rising from fissures in the ground, and lumps of solidified lava could be heaped up above them. These lumps were allowed to remain for one or two days. After that time they became slightly pasty, but no remelting was ever observed.

SPECTROSCOPIC STUDY OF THE VOLCANIC FLAMES.

Mention has already been made in the course of this paper of flames rising from the lava lake, the cones, or the gas vents. The flames at the lava lake were small and relatively rare, but flames at the cones and vents were exceedingly bright, and could be approached within very short distances. When it became apparent after a few weeks that these flames could be considered a permanent feature of the eruption, the writer decided to attempt a spectrographic study of the burning gases. A spectrograph was ordered in Europe, but as it had to be shipped by air-mail and carried by man on the two-day trip from the road up the volcano, considerations of weight and bulk prevailed in the choice of the instrument. Besides, the volcano at that time was showing signs of waning activity and consequently the only suitable instrument was one that could be shipped without delay. The choice was thus rather restricted.

The spectrograph arrived at the writer's camp at the end of June. It was a Hilger constant deviation spectrometer equipped with camera and having a range of 3800-9000 Å.

The instrument was set up in the field, 50 meters from a gas vent, on June 28. Several plates were taken without particularly successful results. On account of the explosive nature of the flames the light was extremely unsteady. Very long exposures had to be made; consequently only very few exposures could be obtained in one night. Furthermore, correct focussing required a great many trial exposures; plates had to be carried back to camp, a mile away, to be developed; clean water was scarce, and the tent was anything but moonlight-proof. The full moon, early in July, interrupted the work.

Work was resumed about a month later, on August 9. A new and more powerful condenser lens had been ordered and received in the meantime, with the hope that the exposures might be cut down. After a few days' work, the gas vent died out, but a new vent had been formed at some distance, in a much less accessible spot. Operations from then on were carried out from the camp, a procedure that offered greater facilities for nightlong exposures and immediate development, using a Leica 150 mm. telephoto lens as a condenser. It was some times a ticklish job to focus properly on the slit the flickering image of the flames half a mile away.

Ilford Panchromatic and Ilford Infra-red plates were used. In order to provide convenient means of determining the wave-

length of the lines in the unknown spectrum of the flames, reference spectra of Argon and hydrogen were photographed on each plate immediately beneath or above the spectrum of the flames. Argon and hydrogen spectra were obtained from Geissler tubes run on a Ruhmkorff coil and batteries. The blue and red light of the Geissler tubes proved unexpectedly popular with the native porters.

At first, exposures of one hour or so were made, the spectrograph being set up at about 50 meters from the flames. On plates taken on July 1 and July 2, three very weak lines were observed around 4400 Å. Increased exposures were made with the hope that these lines might come out better, but exposures as long as eight or ten hours proved unsuccessful. These lines were never registered again.

As a whole, the spectrum of the flames in the range 4000-9000 Å was found to consist of:

- (a) in the visible part of the spectrum:
- 1° Three narrow bands, fading out slightly towards the red, at 4360, 4430, and 4440 Å approximately.
(These bands were found on two plates taken on July 1 and July 2, and never later.)
 - 2° A wide band, beginning at 5700, with two well-marked maxima at 6000 and 6400.
 - 3° The sodium D line. On account of the very low dispersion of the instrument, the two lines register as a single one.
- (b) in the infra-red spectrum:
- 1° The two K 7665 and 7699 lines.
 - 2° A faint line around 8200.
 - 3° A band with its head slightly to the right of the K line and extending towards the infra-red throughout the range of sensitivity of the plate.
 - 4° A band slightly to the left (short wave side) of the K lines.

The plates were sent for examination to the Department of Astrophysics of the University of Liege. Professor Swings and co-workers kindly reported as follows:

“The bands with head near 7630 are the $\Delta v=2$ sequence of the first positive system of N_2 ($^2II \rightarrow ^2\Sigma$); the head corresponds to the band 3,1 and is in accordance with the Frank-Condon rules on distribution of intensity.

“The bands near the Na I line are the $\Delta v=3$ and $\Delta v=4$ groups of the same first positive system of N_2 .

“The maximum intensity to the right of the K line is probably caused by the continuous thermal radiation combined with the sen-

sitometric curve of the plate. A photometric study on better plates might give the temperature.

"The three bands near 4360, 4430, and 4440, fading out towards the red, may not be ascribed to atoms. It has not been possible to identify these bands which, however, may be compared to unidentified bands in spectra of comets.

"The line near 8200 might be the 8194.9 line of Na (?)."

Concerning other substances that might be expected in the flames, Professor Swings writes as follows:

"The OH bands (which would probably be much more intense than the OH₂ bands) are close to 3100 Å, in the ultra violet; they could not be observed with your equipment. The bands of the sulphur compounds are also mostly u.v. Possible bands of C₂, CN, and CH, are mostly from 3800 to 4500 Å, in a range in which I suspect your spectrograph was not accurately focussed or possibly your plates were not quite sensitive enough. In order to obtain really important results, it would be necessary to work in the range 2000-9000 Å with a set of instruments and emulsions, using well thought-out exposures.

"From the plates submitted to my examination, it is not possible to state whether H₂ is present or not in the flames. The only H₂ bands in the range $\lambda > 2000$ Å require very great excitation energies which are not likely to be found in flames."

The occurrence of the N₂ bands is somewhat surprising and puzzling, not that N₂ would be at all unexpected in the gases, but because the excitation potential of the first positive system is close to 9.5 volts. In other words the energy required to produce these bands is very much higher than what would be expected in flames, and thermal excitation alone would probably not account for their occurrence. If thermal excitation in the flames was actually very high, one would expect to find in the spectrum lines of a great many elements which are probably present and which have much lower excitation potentials, such as Ca or Mg, for instance. Professor Swings believes, however, that the material submitted to him does not warrant any statement along these lines.

The problem of the origin of the energy required to excite the N₂ bands is a puzzling one. If this energy is of chemical origin, as it may be, it seems possible that much of the nitrogen in volcanic gases is purely magmatic and not, as it is usually considered to be, of atmospheric origin.

Summing up the results of this investigation, it turns out

that the only lines or bands recorded and identified are those of sodium, potassium, and nitrogen. The excitation of the molecular bands of nitrogen requires a surprisingly large amount of energy, possibly of chemical origin, but which has not been accounted for satisfactorily as yet. Unidentified bands are found around 4400 Å. No immediate conclusion can be derived as yet concerning the composition of the burning gases. In the writer's mind the more important result of this investigation is that the proof is now complete that spectrographic analysis of the flames is by no means an impossible task and, furthermore, that it would be of considerable interest both for geologists and astrophysicists.

Plate I, Fig. 1 reproduces a photograph of the flame spectrum, in the visible range. Imperfect as it is, it is believed to be the first one ever published and may thus be of interest.

GAS DISCHARGE DURING THE ERUPTION.

Having observed for some time the changes in the lava lake and the disconcerting behavior of the gases, and having obtained a sufficient number of temperature measurements, the writer began to doubt the potency of the gases as mechanical or thermal agents. He was very much impressed by the fact that the gases and the lava seemed to have antipathetic relations: where the lava came out in greatest quantities at the source of the stream, no gases were seen to rise, whereas the discharge of lava was absolutely insignificant at places of great emission of gases (cones and gas-vents). In the lake, the gases were rising precisely where the lava was sinking. There seemed to be no relation between the state of activity of the cones and that of the lake; or between the activity in the lake and the discharge in the stream. On the contrary, the more rapid subsidence of the lava in the lake occurred precisely at the time when the gas pressure seemed to be greatest, judged by the activity at the cones and the emission of small flows of pasty lava at the cones, 40 meters above the level of the lava in the lake. Subsidence in the lake could not be connected with variations of the discharge in the stream. This discharge, in turn, seemed to bear no relation to the cones and flaming vents; in fact, it was reported that after the last vent had died out in November, no changes could be observed in the stream. The impression was thus gained that the gases were perhaps as a

whole independent of the lava. These facts were best explained in the writer's mind by the assumption that a very complete separation of phases was taking place at depth in the magma reservoir. This would explain how, from there on to the surface, gases and lava might act almost independently.

Separation of phases in a hypothetical magma reservoir would mean that under the conditions obtained in this reservoir, the magma had become oversaturated with gas. One way of proving the point would be to show that the amount of gases discharged exceeded indeed any amount that could be held in solution in the reservoir at a moderate depth. The writer therefore decided to engage in an estimation of the ratio of the weight of gases to the weight of lava discharged in a given time.

This was by no means an impossible task. The discharge of lava could be estimated from the width of the stream and the speed of the lava, guessing at its depth, and checking the result against the aggregate discharge as obtained by surfacing the area covered by the lava and taking a mean thickness for the flows. Owing to the fact that the gases were rising mainly from discrete localities such as cones and vents, their amount could be estimated with a reasonable accuracy. The cross section of the vents could be determined exactly. The speed of the rising column of gases could be estimated with reference to an object of known height, such as a tree, or calculated from the time of flight of ejectamenta by the well known formula $T = \frac{2v \sin a}{g}$, g being the acceleration of gravity, a the angle (practically 90°) and v the unknown initial speed. Allowance should be made of course for the fact that gas explosions occurred only at regular intervals. When an idea of the discharge at one vent had been obtained in this way, the discharge at other places could be estimated by comparing, under similar atmospheric conditions, the size of the clouds. If the work is done with sufficient care, the results may be correct within 50 or 100 per cent. The reader must be reminded that much of the gases that are seen to rise are derived from the atmosphere (since the burning gases actually combine with oxygen) or contain much steam of meteoric origin. This was not taken into account in the calculations, so that the figures for the emission of gases are possibly much too large.

Once the volume of gases became known, their weight could be computed on the basis of a density of 0.18 kg./m.³ at

1200° C. and 760 mm. Hg. This is approximately the average density of gases from Lassen and Mt. Pelée lavas, as given by Shepherd⁸ and Shepherd and Merwin.⁹

Several determinations were carried out at a few weeks' interval, from July to September. These results were consistent and averaged around 0.7 per cent. Taking into account possible errors, and the fact that a very large proportion of the gases may be derived from the atmosphere,¹⁰ it seems safe to state that at that time, the ratio, in weight, of the gases of magmatic origin to the lava were well below one per cent. The writer fails to recollect any evidence that this ratio might have been larger during the earlier part of the eruption.

Rittmann,¹¹ who has described the 1928 eruption of Vesuvius, was very much impressed by the amount of gases liberated during the eruption. He gave volumetric estimates of the gases and of the lava which, when converted in weight, turned out to be of the same order of magnitude (0.6 per cent). Contrary to Rittmann's impression, this ratio is amazingly small.

UNDERSATURATED MAGMAS.

Let us consider some implications of this result.

The reader should be reminded that there is no evidence that the lava, where it reaches the surface, is oversaturated with respect to surface conditions. The lava comes out without a bubble or a splash, and it flows downhill without giving off much smoke. Where it spreads out in the plains, most of the smoke rising from it may be traced back to burning brush, for wherever one flow solidifies on top of another, there is no emission of smoke at all. The lava solidifies to a moderately vesicular pahoehoe, with a thick skin of solid glass. It seems likely that the lava, where it comes out of the ground, is just saturated, or even undersaturated, with gases.

It is reasonable to assume that the solubility of gases in lava increases with increasing pressure, at least for low values of the gas content. Goranson's well known experiments on water and granitic melts show that this increase in solubility is very

⁸ *Jour. Geol.*, 33, p. 367, 1925.

⁹ *Jour. Geol.*, 35, p. 106, 1927.

¹⁰ It requires 16 gms. of oxygen or approximately 80 gms. of air to burn 2 gms. of hydrogen. A mixture of 22% water and 78% nitrogen would contain less than 3% of gases of magmatic origin.

¹¹ *Zeit. Vulk.*, 12, 305-22, 1930.

great at low concentrations. If his figures hold approximately true for the Nyamlagira gases and lavas,¹² the extra one per cent of gases which escapes at the volcano would become entirely soluble in the lava at a very shallow depth, less than 1 km. In spite of the fact that the volume of one per cent of gases is enormously greater than the volume of 99 per cent of lava, it does not seem probable that the gases could lift the lava from any great depth, as they would soon be dissolved by the pressure in the lava column itself. Once dissolved, their lifting power would be exceedingly small.

Since, however, solubility of gases is known to decrease with increasing temperature, it might be contended that the increase of temperature with depth balances the increase in pressure, and the separation of a gas phase with great lifting power might become possible if very high temperatures in the magma reservoir are granted. But, again, if figures for granite and water hold approximately true in this case, an increase of temperature of several hundred degrees would be necessary and a suitable mechanism should be provided through which the lava might cool down by that amount between the reservoir and the surface. Possibilities for such cooling seem to be out of the question.

A further implication of the very low values found for the discharge of gases is that, if the reservoir is at a depth greater than say, 1 km., the lava in the reservoir may not be saturated with gases unless the extra few per cent required to saturate the magma are escaping unnoticed or are accumulating inside the volcano, an improbable hypothesis.

Since figures for the gas/lava ratio are approximately the same for Vesuvius and Nyamlagira, this might be a general state of affairs with volcanoes. We are thus faced with the disturbing suggestion that magmas inside volcanoes might not be saturated with gases.

An alternative explanation is that the increase of solubility with pressure in the case of basic magmas and volcanic gases is much smaller than in the case of granitic melts and water. Experiments should decide whether it is possible that basic lavas containing less than one per cent volatile constituents in

¹² The chemical composition of the lavas of the 1938 eruption is not known yet. Holmes and Harwood (Geol. Surv. Uganda. Mem. III, Part II, 1937) describe the lavas from Nyamlagira as being mostly kivitites (SiO₂ around 43%).

excess of the amount soluble at atmospheric pressure can become oversaturated with gases at a pressure corresponding to a depth of a few kilometers.

It does not seem advisable, at this stage of investigations at Nyamtagira, to draw any conclusions or make sweeping statements concerning gases and volcanic activity. The writer wishes merely to draw attention to the occurrence in Africa of a volcano of unusual characteristics, offering exceptionally favorable conditions for continuous observation. The impression was gained after a few months' work at this volcano that possibly gases are not as essential to the mechanics of Hawaiian volcanoes as was previously believed.

A detailed report on the 1938 eruption is being prepared for publication in the series of the "Institut des Parcs Nationaux du Congo Belge," Brussels, Belgium.

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