COMMONWEALTH OF AUSTRALIA.

DEPARTMENT OF NATIONAL DEVELOPMENT.
BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

BULLETIN No. 38.

THE 1951 ERUPTION OF MOUNT LAMINGTON, PAPUA

BY

G. A. TAYLOR, G.C.

Complimentary

Issued under the Authority of Senator the Honourable W. H. Spooner, Minister for National Development.

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Minister: SENATOR THE HON. W. H. SPOONER, M.M.

Secretary: H. G. RAGGATT, C.B.E.

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS.

Director: P. B. NYE, O.B.E.

Deputy Director: J. M. RAYNER.

This Bulletin was prepared in the Geological Section.

Chief Geologist: N. H. FISHER.

ERRATA.

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p. 17, line 3: for " fig. 9 " read " fig. 8 ".

p. 27, line 20, should read: " dark, but it did not appear to be black as in the morning eruption. The roar became ".

p. 52, line 17: for " fig. 84 " read " fig. 81 ".

p. 57, line 15: for " fig. 63 " read " fig. 103 ".

p. 58, line 12: for " figures 149 and 150 " read " figures 154 and 155 ".

p. 70, line 3 from bottom: for " 141a " read " 146 ".

p. 71, line 12 should read: " Light-grey andesite prophyritic in plagioclase, brown hornblende, biotite, pyroxene,".

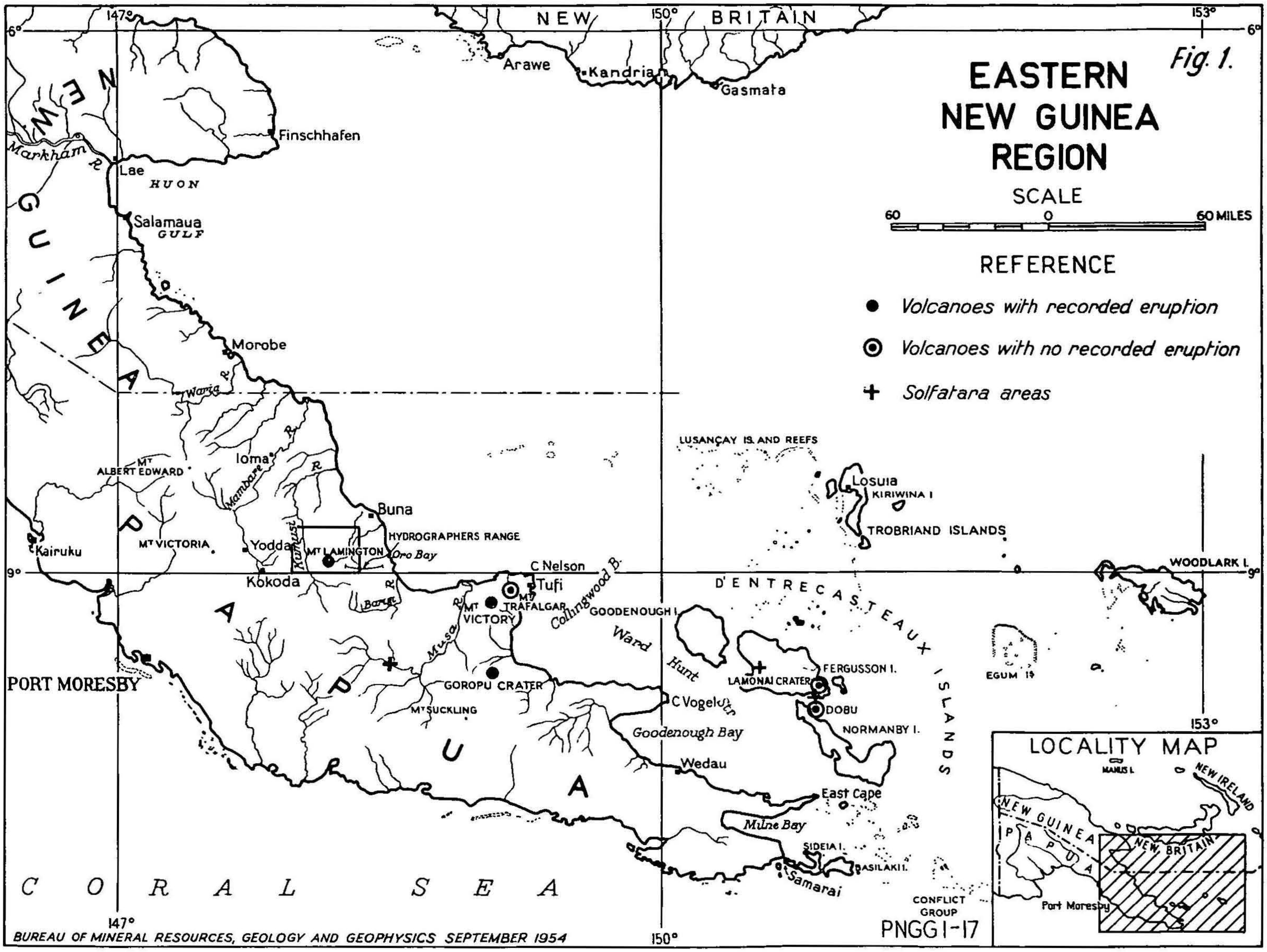
p. 76, line 4: for " magnetic " read " magnetitic ".

p. 89, line 36: for " fig. 13 " read " fig. 15 ".

p. 91, line 39: for " 1959 " read " 1949 ".

p. 101, line 1: for " fig. 151 " read " fig. 156 ".

p. 107, line 2 from bottom: for " Figure 153 " read " photograph ".


EASTERN NEW GUINEA REGION
Fig. 1.
SCALE
60 0 60 MILES
REFERENCE
Volcanoes with recorded eruption
Volcanoes with no recorded eruption
Solfatara areas
NEW BRITAIN
Arawe
Kandria
Gasmata
NEW GUINEA
Markham R
Finschhafen
Lae
HUON GULF
Salamaua
Morobe
Waria R
Mambare R
Ioma
MT ALBERT EDWARD
MT VICTORIA
Yodda
Kokoda
Kumusi R
Buna
HYDROGRAPHERS RANGE
MT LAMINGTON
Oro Bay
Kairuku
PORT MORESBY
PAPUA
C Nelson
Tufi
MT TRAFALGAR
MT VICTORY
Musa R
Collingwood B.
GOROPU CRATER
MT SUCKLING
Ward Hunt Str
C Vogel
Goodenough Bay
Wedau
East Cape
Milne Bay
Samarai
SIDEIA I.
BASILAKI I.
CONFLICT GROUP
GOODENOUGH I.
FERGUSSON I.
LAMONAI CRATER
DOBU
NORMANBY I.
D'ENTRECASTEAUX ISLANDS
LUSANÇAY IS. AND REEFS
Losuia
KIRIWINA I
TROBRIAND ISLANDS
WOODLARK I.
EGUM I.
CORAL SEA
LOCALITY MAP
MANUS I.
NEW IRELAND
NEW GUINEA
PAPUA
NEW BRITAIN
Port Moresby
147°
150°
153°
6°
9°
BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS SEPTEMBER 1954
PNGG 1-17

FOREWORD.

The Peléan type of volcanic eruption, with its swift and deadly cloud of hot, gas-charged particles, was first brought to the attention of a horrified world in 1902, when 29,000 people perished in a few minutes in the morning of May 8th, at St. Pierre on Martinique in the West Indies, only sixteen hours after an eruption of the same type at La Soufrière on nearby St. Vincent had killed 1,650 of the inhabitants and devastated a large area of that island.

These eruptions were described by Lacroix, Hovey, Anderson, Flett, and others, and since then several eminent vulcanologists have studied and reported on this fortunately fairly rare type of volcanic activity and the phenomena associated with it. Notable amongst these later works are Fenner's description of the Valley of Ten Thousand Smokes at Mt. Katmai in Alaska, Perret's masterly analysis of the eruptions of Mont Pelée in 1929-32, and the work Stehn and Neumann van Padang in the East Indies.

The Mt. Lamington eruption which is the subject of this bulletin is one of the most outstanding examples of the Pelean type of eruption that has occurred in historic times. It was remarkable both as a manifestation of volcanic violence and because of the character and calibre of the observations that were subsequently made.

The area had no volcanic history; local native folk lore contained no legend of eruption, nor were any surface expressions of volcanic activity known in the area. Mt. Lamington was not merely regarded as extinct—it was not even considered as a volcano at all. The presence of a crater had not been recognized—it had never been examined by a geologist—and, being completely open on the northern side, it appeared only as one of the heads of the stream system of the Ambogo river, which rises in a series of rugged hills.

It is doubtful if the violence of the eruption itself has been exceeded in modern times by any observed Peléan-type eruption, although Mount Pelée had a more impressive record of human destruction, owing to the particularly vulnerable position of the town of St. Pierre with respect to the crater.

Opportunities for recording the phenomena associated with the Mt. Lamington eruption were exceptional: the main outburst was observed and photographed from a passing aircraft at close (almost too close) quarters. A qualified vulcanologist began recording events on the spot barely 24 hours after the main explosion, and observations were continuous from then onwards. A sensitive seismograph was installed at Sangara plantation, 8½ miles from the crater, within eighteen days of the eruption. Skilfully manned aircraft were available for daily inspection, photography and recording of crater phenomena and dome growth. The full co-operation and support of the administrative authorities were accorded throughout the investigation to vulcanologist Taylor and the other scientists associated with him. Several reliable observers living 8 to 10 miles from the crater survived the blast and provided details of the eruption and of pre-eruption events.

The author of this Bulletin, who combines a fearless devotion in the field to his fascinating but unruly subject with a considerable talent for narrative writing, has supplemented his detailed observations of the progress of the eruptive series with painstaking analysis of a mass of seismograph and other records. The results presented in this Bulletin constitute an important contribution to the literature of volcanoes and volcanic processes.

N. H. FISHER,
Chief Geologist.

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SUMMARY.

When Mount Lamington erupted in 1951 a long-dormant volcano sprang suddenly into life and produced a paroxysmal outburst of disastrous proportions. Its resemblance to Mont Pelée was most marked, both in the form of its cone and the pattern of its activity.

Mount Lamington rises nearly 6,000 feet above the northern coastal plane of Papua, which is formed, in part, of the uplifted marginal Tertiary sediments of the Cape Vogel Basin. Although frequent and intense volcanic activity has occurred in the past in this eastern region of Papua, few eruptions have taken place in historic time. Goropu erupted in 1943 and most probably Mount Victory was active during the last century.

The wide cone of the volcano is composed predominantly of fragmental material and the slopes rise gradually to a rugged summit nucleus buttressed by viscous flows and protrusions. The crater walls are composed mainly of remnants of earlier protrusions and in places they rise almost 2,000 feet above the old crater floor. The symmetry of the crater is broken by a deep notch on the south-eastern side and by the absence of a wall on the northern side, which is open to an "avalanche valley" of such broad proportions that the immediate post-eruption crater seemed to form the upper end of the valley. The pre-eruption crater was partly filled by a small dome which was destroyed by the climactic explosions.

Poorly bedded and chaotic deposits ranging in texture from tuffs to agglomerates predominated in the fragmental material of the cone. Massive deposits of earlier nuées were fairly common. That the Pelean type of eruption is a long-established mode of activity for this volcano is suggested by the discovery of an old eruption surface in the valley walls of the entrenched Ambogo River; it is at least 100 feet below the surface of the present cone. An age determination carried out on a piece of carbonized wood from a neighbouring valley indicates that Pelean activity possibly occurred 13,000 years ago. However, Lamington had not been active within historic time, nor did the natives living on the slopes of the unrecognized volcano have any legend of an earlier eruption.

Reactivation of the volcano began with six days of preliminary phenomena which culminated in a catastrophic explosion. This preliminary activity consisted of landslides in the crater area, earthquake swarms, and emissions of gas and ash which increased daily. At 1040 hours on Sunday, 21st January, 1951, a paroxysmal explosion burst from the crater and produced a nuée ardente which completely devastated a surrounding area of about 68 square miles. Almost 3,000 people perished in this area. Further violent explosions followed within the next twelve hours.

The climactic explosions were followed by other powerful outbursts which ended rather abruptly early in March, when the large dome which had been rising in the crater since late January was explosively destroyed. This event ended the highly explosive phase of the volcano's activity, although smaller explosions occurred until the end of June. After the March eruption the activity became predominantly effusive and the long process of dome building was firmly established.

Explosions ranged from powerful projections of the normal vulcanian type to weakly projected "shallow-pocket" disgorgements. The powerful projections rained

ejecta over the surrounding country and the "shallow-pocket" disgorgements merely discharged masses of gas-emitting fragmental lava on to adjacent slopes. Ultimately these shallow-pocket discharges appeared to pass into the pulses of extrusive activity which precipitated avalanches down the flanks of the dome. Some of the eruptions were "mixed" outbursts, that is, some material was ejected vertically and the remainder was discharged on to the slopes to form a nuée ardente. Despite the presence of a dome and other similarities with Pelée no evidence was found to support the hypothesis of horizontally directed explosions.

The catastrophic nuée ardente of 21st January descended radially from the crater and devastated an area of about 90 square miles. The form of the crater and the topography of the slopes were important factors in limiting the extent of the nuée, which was restricted to 6-8 miles on the northern slopes and to 4-5 miles on the southern slopes. Its direction of movement was governed basically by topography, but some movements were due to unrelated turbulence which formed vertical vortices. A conspicuous effect of the passage of the nuées was an abrasive action; grooving and scouring of the soil surfaces occurred in areas close to the crater. Some effects were sufficiently severe to leave in the land-form a change which could be recognized long after the eruption. A study of plastic and other objects recovered from settlements about 6 miles from the crater suggested temperatures in the nuée to be of the order of 200° C., lasting for 1½ minutes. Erratic temperature distributions in the thick valley deposits suggested that much of this nuée material fell below charring temperatures before it lost its mobility. That the mobility of the nuée was derived from gas emitted by a molten green-hornblende-bearing magma which also formed pumices was suggested by a predominance of green hornblende in the ash which rose from a descending nuée ardente. Additional gas may have been supplied by the expansion of compressed gas held in the pores of solidified material.

The lethal effect of the nuée ardente seemed to be due mainly to sudden damage to the respiratory system caused by inhaling hot dust. Some deaths were caused by cadaveric spasm.

Vegetation was quick to recover in the devastated areas. Root crops of native garden areas were beginning to penetrate the blanket of ash a few days after the climactic eruption. Indigenous grasses were slower but new growth was vigorous and profuse.

The deposition of ash fell into three categories; deposits from vulcanian explosions were thin and widespread; thick deposits from the "ash hurricane" component of the nuées ardentes were confined mainly to the devastated area; and massive deposits of the ash-flow type were strictly confined to the valleys radiating from the crater. The distribution of the deposits suggests that either extremely powerful vulcanian explosions or sustained mobility in a nuée ardente may upset the conventional thickening of deposits close to the crater. Observation of the draining of ash flows from the upper part of their course throws doubt on the validity of Lacroix' principal argument for the occurrence of horizontally directed explosions.

The interaction of surface waters with hot ash beds surrounding the volcano caused secondary activity, which was a conspicuous aftermath of the Pelean explosions. Some of these secondary outbursts could easily have been mistaken for external vents. Secondary activity was closely associated with mudflows which rapidly removed the ash deposits from the valleys. These viscous torrents of debris scoured the valleys, destroyed communications, and buried some of the lower garden land. The most serious effect was the silting of streams and a consequent flooding of marginal land, The opaque minerals in specimens of the old lavas were magnetite, titanium-rich magnetite, pyrite, chalcopyrite, and chromite.

Sublimation products were not deposited in conspicuous amounts in the Lamington crater. Gypsum, the most abundant mineral, was formed around the dome vents and in the nuée deposits. Sulphur, aragonite, aluminium phosphate, and α-cristobalite were identified.

Although tectonic earthquakes are not numerous in the eastern region of Papua the broad picture of events in the adjacent island regions suggests that the Mount Lamington eruption was triggered by a crustal stress pulse. The stress pulse was manifest in an increase in the frequency of tectonic earthquakes and reactivation of volcanic centres in New Guinea, the Solomon Islands, and the New Hebrides.

Localized volcanic earthquakes were a conspicuous feature of the actual eruption. Earthquake swarms preceded the early climactic outbursts and the later explosive activity had a background of consistently high and fluctuating seismicity. Local earthquakes continued long after explosive activity had ceased.

Tilt measurements, which began in April, suggested swelling of the mountain before the main extrusive movements. An extraordinary fall and rise of tilt occurred towards the end of 1952. It was not accompanied or followed by marked change of volcanic activity.

During critical conditions of the volcano's activity, when the eruptive forces seemed to be nicely balanced by the restraining forces of the viscous magma, the volcano responded to the tidal effects of the sun and moon. Intense activity near positions of maximum lunar declination suggested that the direction of the tractive force was as important as the magnitude of the tidal force.

The conduit lava rose into the crater soon after the climactic explosions, to form a dome which, in less than two months, stood more than 1,500 feet above the crater floor. Early in March this structure was mostly destroyed by explosions, but quickly grew again, and by January 1952 the protrusion was 1,900 feet high. Subsequently its bulk increased and its height was reduced to about 1,850 feet. Its final volume of a quarter of a cubic mile made it the largest protrusion whose growth has been actually witnessed. After the dome was destroyed the mode of extrusion changed. In its early stages the dome moved in a piston-like fashion over the full width of the crater, but later it grew in a piecemeal manner by extrusions localized in time and place. These irregular movements made easy the appreciation of the reason for a lack of internal structure which is characteristic of the Pelean dome. The final structure had the normal truncated-cone shape common for such structures and gave no hint of the irregular mode of its growth.

The dome was made up of three principal types of lava: type I., lamprobrolite andesite, type II., olivine-pyroxene-anhydrite-lamprobrolite andesite, and type III., anhydrite-hornblende andesite.

Type II. is the most common lava and the other types are localized in their distribution. Type I. when found in situ was associated with cavities and fractures in the dome. Type III. appeared in a late phase of the extrusion when the movement became confined to the centre of the conduit. Ultrabasic rocks are common among the inclusions in the lava. Extrusion processes in the dome yielded fine-grained friction breccias and stressed rocks showing " gneissic " banding and a lineation formed by pipes of shattered crystals.

The fragmental material ejected by the volcano consisted of both new and old lavas. A glassy green-hornblende andesite with a mineralogical composition similar to that of the type III. lava was the most active agent in the eruptive mechanism; it formed pumices and was the predominant constituent of the ash ejected great distances as well as of the ash which rose from a descending nuée. Ash from the thick nuée deposits in the valleys, on the other hand, was composed chiefly of old lavas.

Except for the old flow lavas, which have a higher proportion of groundmass, the lavas of the volcano contain about equal proportions of phenocrysts and groundmass. Plagioclase is the most abundant mineral among the phenocrysts. The feldspar of the recent eruption is slightly more acid than that of the earlier lavas. The proportion of hornblende, or more correctly amphibole, phenocrysts rises as high as 19 per cent. This pressure- and temperature-sensitive mineral appears in a variety of forms. In the flow rocks it shows advanced and complete " resorption " or reconstitution of the magnetitic type; in the dome rocks the " resorption " may be advanced or absent. " Resorption " of the amphibole in the new dome lavas is rare, but the varieties range from green hornblende to the bright red-brown lamprobrolite. Biotite occurs in the same rocks as the amphibole and it exhibits similar oxidation and " resorption " properties. The amount of biotite in the new lavas ranges from 4 per cent. to 1 per cent. Pyroxenes are most abundant where hornblende and biotite are greatly altered, or absent, and rarely occur in the glassy green, hornblende-bearing andesites. Other common phenocrysts are olivine, magnetite, and anhydrite. The groundmass of the lavas ranges in texture from almost holocrystalline in the old flows to the few microlites and abundant glass of the pumices; the microcrystalline and glassy groundmass of the dome lavas is a texture midway between these two extremes. The porosity of the lavas is related largely to the amount of glass in the groundmass.

INTRODUCTION.

Before the Second World War the Territories of Papua and New Guinea were separately administered and as a result the vulcanological survey which was instituted after the 1937 eruption at Rabaul covered only the volcanic centres of the New Guinea Territory. When, therefore, on 19th January, 1951, the news services announced an eruption in Papua of a new volcano, the exact location of Mount Lamington was uncertain. This uncertainty was further increased when a radio message from the Lamington area, intercepted at Rabaul, placed the centre of activity near Tufi, many miles to the east.

At that time I was stationed at Rabaul and had been carrying out vulcanological observations on the New Guinea volcanoes for almost a year. When the news of this new activity in Papua was heard, approval was obtained from the Administrator, His Honour Colonel J. K. Murray, to investigate it as soon as possible. The first available air service to connect with one to the Lamington area departed from Rabaul early on the morning of 22nd January. About an hour after departure a radio message brought tragic news. On the previous day Mount Lamington had produced a disastrous eruption with many casualties: dust from the volcano was still falling over the Port Moresby area and the aerodrome was closed to traffic. The Administrator, who was aboard the aircraft, requested a diversion over the Lamington area before proceeding to the alternative aerodrome at Lae.

A pall of dust hung over the area, completely concealing the summit of the volcano, and so poor was the visibility that only brief and partial glimpses of the extraordinary area of devastation were obtained near the mountain. Dust and the acrid odour of sulphur dioxide permeated the aircraft. A more detailed air survey of the area was made about three hours later from a small Drover aircraft in company of the Administrator, the Director of Health, Dr. Gunther, and a native assistant, Leslie Topue. The party landed at the Popondetta airstrip just after midday, a little more than 24 hours after the great outburst had occurred.

The following account of the Mount Lamington eruption is based on almost two years of observation which began at this early stage of the eruptive activity. Daily aerial crater inspections enabled the course of this Peléan type eruption, the most lethal of all volcanic manifestations, to be uniquely charted. Perhaps this detailed study will help to unravel some of the controversial issues which have arisen since the phenomenon was first recognized at the turn of the century in the eruptions of Mont Pelée and Saint Vincent. I was present for all the main active phases of the post climactic period and was absent only when circumstances demanded investigation of other centres. One of these investigations, carried out at the request of the Administration of the New Hebrides Islands, was most important in that my experience was enlarged by the study of a volcano of a completely different type—Ambrym volcano in the New Hebrides Islands. This volcano has many of the characteristics of Vesuvius in its mode of activity, and the extraordinary eruption of 1950-1951 was one of those rare opportunities that come to a worker in this field to study a large-scale eruption of this type and with this experience to come to a fuller appreciation of the significance of external factors in the mechanism of these energy systems.

Further experience was gained by the study of Mount Bagana, which produced glowing clouds in the eruption of 1950, and by investigating the precursory events of the Mount Langila eruption which began at least two years before its culmination in 1954. The work on these centres and later on Long Island and Bam volcanoes served to confirm some of the ideas which were merely suggested as possibilities in the study of the Mount Lamington eruption. A visit to New Zealand in 1953 and the kind assistance of Mr. J. Healy of the Geological Survey served to make me familiar with the vast glowing cloud deposits of that country and removed any temptation to identify the phenomena as a condition of volcanic decadence.

In the observation work and collection of data on this eruption I have been liberally assisted on every hand.

The many government officers concerned with the eruption were unsparing in their efforts to satisfy the demands of this scientific work, and a similar response came from the private citizens and missions of the district. The daily crater flights were undertaken for the first week by pilots of the Department of Civil Aviation and afterwards by QANTAS pilots. The skill and daring of these men took us safely into the almost unknown territory of an active Pelean crater and made close observation possible. The names of all those who have helped would fill a small volume, so it is only possible to mention a few, and to the others to say that their help is most gratefully acknowledged. Particularly do I wish to thank Colonel J. K. Murray, B.A., B.Sc.Agr., who was Administrator at the time of the eruption. His practical support and scientific appreciation did so much to facilitate the study of the eruption and his personal courage set an example during the critical days of the activity. This assistance was continued in the latter period of the eruption by his successor, His Honour Brigadier D. M. Cleland, C.B.E., whose help is deeply appreciated. I am indebted to Dr. N. H. Fisher, Chief Geologist of the Bureau, for his guidance and encouragement during the " black " days when explosive potential was high and for his personal understanding of problems which sometimes confront a scientist. The operation of the seismograph and the maintenance of routine instrumental readings fell largely on the shoulders of W. J. Langron, of the Bureau, whose highly commendable diligence and long hours of duty contributed much of the valuable instrumental data of the eruption. Assistance in instrument operation was obtained for short periods from F. R. Walker, P. Harbeck and S. T. Rohde. Leslie Topue, B.E.M., proved a sterling assistant in the routine of the Observatory Post. Nor can this occasion pass without expressing deep appreciation of the unfailing kindness, patience, and truly gracious hospitality of Mr. and Mrs. T. G. Henderson, who, at Sangara Plantation, had the doubtful privilege of accommodating for almost two years seemingly obsessed addicts to a scientific cause.

As a measure of the morale and calibre of the people who inhabit these isolated communities of the Territory, I should like to draw attention to the fact that little more than an hour after the catastrophic eruption of 21st January and long before news of the event had reached the outside world, a handful of survivors from the marginal settlements found their way into the dust-fogged area of devastation and began to evacuate the wounded.

Finally, I wish to pay tribute to the courage and fortitude of all those who worked in the Lamington area during the emergency. Long hours, arduous duties and an abiding fear of further eruption were all met with an infectious spirit of courage and self-sacrifice which was an inspiration to those whose duty lay in the area.

LOCATION AND GEOLOGY.

Mount Lamington, latitude 8° 56′ S., longitude 148° 10′ E., lies about 25 miles inland from the north-eastern coast of Papua (frontispiece). The mountain rises from a coastal plain of alluvial detritus, derived chiefly from the rugged Owen Stanley Range. This range extends throughout the length of the narrow eastern portion of the island of New Guinea and rises in places to more than 13,000 feet. It is composed of metamorphic rocks, extensively intruded by pre-Tertiary gabbros and peridotites near Lamington, and to a lesser extent by acid porphyries. West of the volcano and on the northern side of the Kokoda valley, the Ajura Kiljala Range consists of metamorphics intruded by serpentinized peridotite and dunite, olivine gabbro, olivine-hypersthene gabbro, hornblende gabbro, augite norite, and hypersthene dolerite; to the south the Guaya Range is composed partly of peridotite and dunite.

Since early Tertiary time the north-eastern flank of the Owen Stanley Range has shed sediments into the Cape Vogel Basin, a trough which is essentially marginal to the present coast. Uplift has exposed portions of the Basin sediments along the north-eastern coast, particularly at Cape Vogel, where several thousand feet of gently folded trough sediments are exposed. Other outcrops have been identified along the coast as far west as Hercules Bay, near Morobe.

Tectonic movement in the Lamington part of the Basin has confined sedimentation chiefly to the Lower Tertiary and Pliocene times. Locally the basement is covered by Lower Tertiary volcanic ejecta and tuffaceous sandstones which are overlain by a thinly distributed lower Miocene limestone. A subsequent depositional hiatus lasted until, in Pliocene time, thin beds of conglomerate, sandstone, and mudstone were deposited. In late Pliocene or early Pleistocene time folding, warping, and faulting movements took place, and Paterson (1955) considers that these late tectonic movements were probably responsible for the formation of a lake in the fault trough of the Kokoda-Yodda valley and for the recrudescence of vulcanism in this part of the Basin.

The revival of volcanic activity apparently found its earliest and most powerful expressions east of Lamington at centres which have erected that complex volcanic pile, the Hydrographer Range. This range, composed of tuffs overlain by agglomerates and flows of andesitic and basaltic lava, rises more than 6,000 feet above sea level and extends from the coast near Oro Bay to the eastern margin of Lamington.

The deep dissection of the Hydrographer Range indicates that most of the activity took place in Pleistocene time; but the presence of a number of perfectly preserved cones and explosion craters on the southern side of the range near the headwaters of the Bariji River suggests that some activity had taken place during Recent time. A linear group of three grass-covered cinder cones lies on a bearing of 237° magnetic from Lamington, and nearby are large sheer-sided craters which appear to be of the steam-explosion type. Other small well-preserved cones are situated on the high country overlooking Songade village on the coast. These cones are forest-covered and are not as evident from the air as the inland structures.

REGIONAL VULCANISM.

In addition to the Lamington-Hydrographer area two main volcanic groups occur in the Cape Vogel Basin, both of which have probably been active in Recent time. The more easterly group includes the volcanic centres of the D'Entrecasteaux Islands; the other group, Cape Nelson, lies about 90 miles south-east of Lamington.

The D'Entrecasteaux Islands contain a number of volcanic cones and extensive thermal areas, most of them on Ferguson Island. Although no eruptions have been reported from this area in the short period of its recorded history, the state of preservation of some of the cone structures suggests that they have been active within Recent time.

The Cape Nelson peninsula is made up of two large volcanic cones, Mount Trafalgar and Mount Victory. Mount Trafalgar is deeply dissected and has obviously been inactive for a long time. Mount Victory rises more than 6,000 feet above sea level and the summit of the well-defined cone is a rugged area covered with vegetation. The irregular form of the summit and the presence of a monolithic " spine " on the southern side suggest that it may be composed, in part, of viscous protrusions. Thermal activity is confined mainly to the north-eastern side of the summit on either side of an elongated depression trending south-west and containing a small lake. Small vents around the margin of this structure emit thin clouds of vapour which are barely perceptible even by close inspection from an aircraft. History records eruption from this volcano during the last century, and that eruption has occurred within the living memory of the local natives is certain as they tell vivid stories of an outburst which was possibly of the glowing cloud type. Further, Mr. W. B. Taylor, botanist attached to a Commonwealth Scientific and Industrial Research Organization Land Research and Regional Survey party, has informed me that sharp changes in the ecology of the vegetation on the lower slopes of the mountain have been observed. Such changes may have been produced by the devastating effect of a nuée ardente, since, typically, the marginal limits of this phenomenon are sharply defined.

The most recently formed volcano in the Territory of Papua and New Guinea is about 30 miles south-south-east of Mount Victory at the foot of the Goropu Mountains. Here a major active fault determines the margin of the mountain range facing the north-eastern coast. Debris brought down by the rapid streams dissecting the contorted metamorphic rocks of this range has partly buried several small extinct volcanic cones near the coast and has formed a coastal plain about 15 miles wide. The plain rises evenly from the coast to the base of the scarp, where its height is about 1,400 feet. The recent activity originated from the rear section of this coastal plain and so close to the fault scarp that the small cone of fragmental material rests against it. The cone was constructed by a series of violently explosive outbursts which began in December, 1943, and continued spasmodically for almost a year. The early activity originated from three adjacent vents, disposed linearly, but the present form of the cone suggests that the central vent became the main source of activity.

The most interesting point revealed by an examination of the Goropu volcano is that this new centre, the activity of which was so close in time to the Lamington eruption, undoubtedly produced nuées ardentes. The rain forest was completely destroyed over a radius of about 2 miles around the gently sloping sectors of the central cone, and the margins of this devastated area are abrupt and clearly defined except in sectors where secondary mudflows have caused additional destruction of the vegetation. The Goropu lava has petrological affinities with that of Lamington; it is a granular porphyritic type of andesite with a slightly lower silica content (55 per cent.) than the average Lamington lava. The phenocryst assemblage of ferromagnesian minerals—hornblende, biotite, augite, and olivine—is common to both lavas. The Goropu lava, unlike that of Lamington, carries a great abundance of metamorphic rock xenoliths.

HOT SPRINGS.

At both Goropu and Lamington hot springs have appeared since the recent outbursts, but before the eruptions thermal activity was not a conspicuous feature either of the volcanic areas or of the mainland region generally; the few that existed may have been associated with tectonic rather than past volcanic activity.

Pre-eruption thermal areas apparently did exist at Lamington, although their presence was not widely known. Natives claim that on the northern slopes a hot spring existed in the valley of the Gawana River but no mention is made of the more extensive thermal area on the southern side of the crater. The presence of these southern hot points is clearly revealed in air photographs taken in 1947. They are grouped around the outside flank of the southern "*piton*" or dome remnant which formed the southern wall of the crater. Some of these thermal points became active again after the eruption.

The other thermal areas reported in the region are possibly associated with recently active faults. The largest group is in the Moni River valley of the upper Musa River system, where four mildly active areas have been discovered. Hot springs reported to exist near the village of Biniguna, about 15 miles south-east of the Goropu volcano, are evidently associated with the same fault as has been responsible for the location of the Goropu vents.

THE STRUCTURE OF THE LAMINGTON CONE.

The Lamington Cone, whose summit is about 5,900 feet above sea level, is a broad gently sloping structure which rises gradually from the coastal plain to a resistant summit nucleus composed essentially of viscous protrusions, flows, and agglomerates (fig. 2). The lower part of the cone, up to about 3,500 feet, is composed mainly of unconsolidated tuffs and agglomerates. These have been so distributed by volcanic activity and subsequent erosion that the unconfined northern and western flanks have extensive gentle slopes; but on the eastern and southern flanks, where the outer margins of the cone are limited by the Hydrographer and Guaya Ranges, the structure loses its smoothness. Parts of these slopes are covered by resistant flows or consolidated tuffs which have been dissected into areas of broken country; the most rugged area lies in the south-eastern sector of the cone between the headwaters of the Girua and Indo Rivers.

The upper part of the cone rises quite abruptly from the gentler slopes below it. This resistant terminal nucleus of the volcano is dominated by a group of ragged peaks formed from ancient remnants of earlier domes and of crater walls. These structures are so disposed that the latest crater is U-shaped in plan; the open side of the U faces the north and is connected to the lower slopes by a broad avalanche valley which has been eroded from the flow-buttressed upper part of the cone (fig. 3). The floor of the crater is about 4,000 feet above sea level and its diameter at the rim is about 4,000 feet. On the eastern side of the crater are two adjacent peaks; the more easterly one, composed of old flows and agglomerates, represents an ancient crater wall; the other is the remnant of an old dome which forms the massive eastern wall of the present crater. The southern wall, which is separated from the eastern wall by a low gap, is formed by a massive protrusion rising very abruptly from the lower slopes to a sharp peak which has an altitude of about 5,900 feet. The highest point is at the eastern end adjacent to the gap; to the west the sheer-sided wall falls to a broad ash-filled saddle before it joins the western wall. The structure of the western side of the crater is more complex: the massive aspect of its southern end suggests a dome remnant; and at the northern end clearly defined flows appear in the crater wall (see fig. 124). In this upper north-western sector of the volcano the outside slopes are covered with lava flows, some of which are of the short viscous coulée type with a flat-topped bevelled profile (see figs. 4 and 55). The largest of the flows extends to the north-west just north of the headwaters of the Embara River, and its comparatively thin cover of ejectamenta and rounded undissected form suggest emplacement at a very late stage in the history of the volcano. Other more dissected flows constitute the base of the western side of the summit nucleus. One of the older flows is revealed in the western wall of the avalanche valley (fig. 5), where the extension of the summit nucleus in this direction is evidently due to the protection given to the unconsolidated agglomerates by this interbedded flow.

Dykes are not a very prominent feature of the upper part of the cone. One intrudes the material in the lower end of the avalanche valley (fig. 6), where there is a sudden drop from the valley floor to the lower slopes. Less than a mile below the summit nucleus the Ambogo has cut part of its gorge into an old cone surface composed of a weathered and well compacted agglomerate which is intruded by a dyke of fine-grained dolerite.

Parasitic structures on the outer slopes supply ample evidence of intrusive activity in spite of the apparent scarcity of dykes in the central nucleus of the volcano. The abruptness with which they rise from the slopes suggests that many of them are domes rather than cones of fragmental material, and they are most numerous on the western flanks of the volcano. Here there appear to be two groups of them: a group of four hills outside the blast area aligned roughly north-south*, and an irregular group of smaller conical hills closer to the base of the central nucleus. The broad sweep on the north-eastern slopes is broken by a very prominent elongated hill which rises more than 500 feet above the surrounding terrain. No crater is preserved at its summit. The most recently formed structure is probably a steep forest-covered cone on the south-eastern slopes of the volcano near Gora village. A perfectly preserved summit crater is clearly discernible from the air.

FRAGMENTAL MATERIAL OF THE CONE.

Most of the cone is composed of unconsolidated tuffs and agglomerates. Much of the material has evidently been laid down rapidly in large unsorted masses by nuées ardentes or by mud-flows, and thinly bedded deposits are the exception rather than the rule over an extensive area around the crater. Only on the outskirts of the cone, at distances which have enabled some fluviatile sorting to take place, does regular bedding appear to be common.

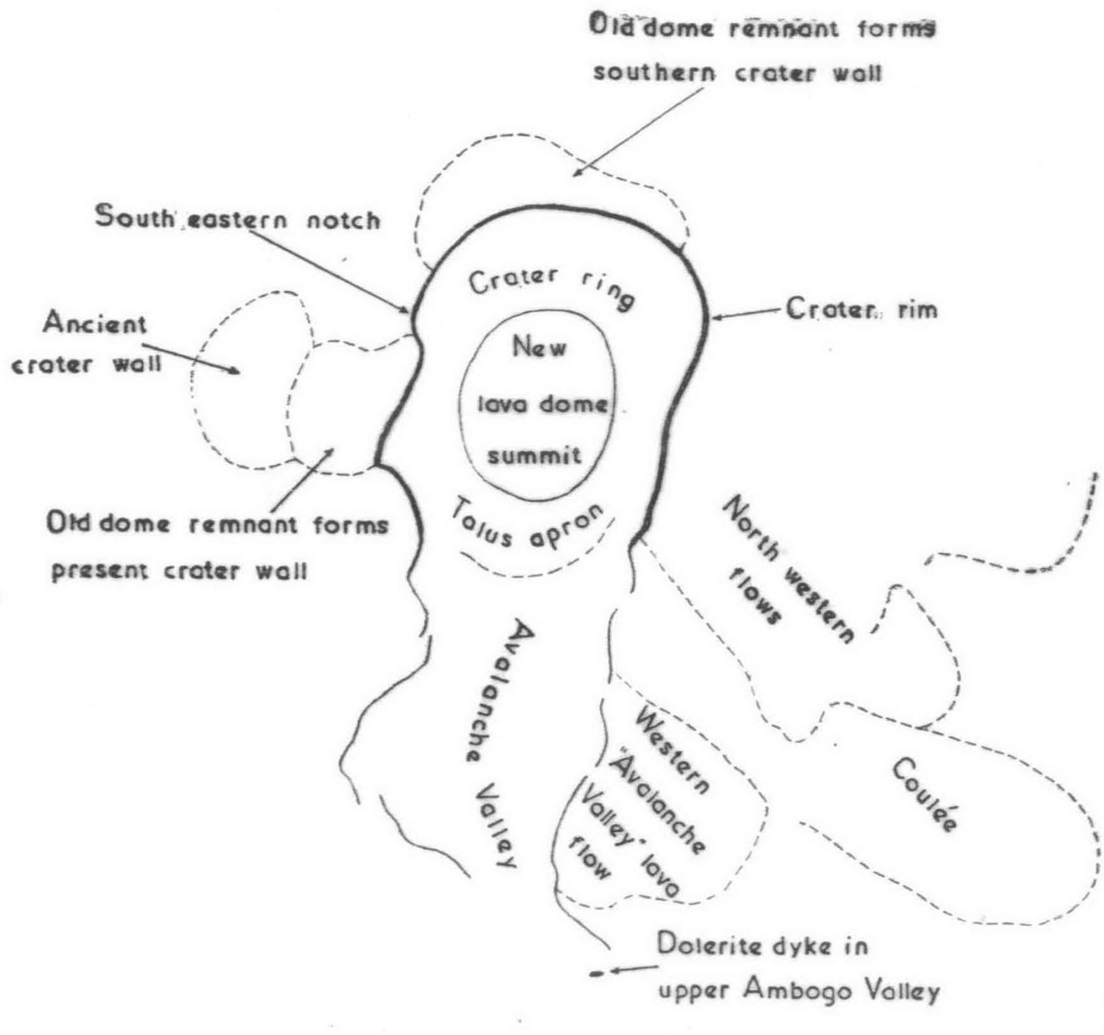
This distribution of material can be illustrated by sections revealed in the Ambogo River gorge. Just below the summit nucleus where the Ambogo River leaves the avalanche valley it has incised a vertical canyon in the fragmental material of the cone. Fig. 7 illustrates the roughness of the bedding in the chaotic deposits. It is not uncommon in this part of the gorge to find sections revealing completely unbedded homogeneous deposits composed of relatively small fragments. Each deposit may have quite a limited lateral extension, and represents material from a nuée ardente which had filled the valley of an old erosional surface. Such a deposit is illustrated in fig. 9, which reveals the absence of large blocks and the uneven base of the deposit.

* The most southern member of this group seems to be part of another linear group of cones which is more or less parallel to the Mamama River, that is, at right angles to the north-south trending line of cones.

Fig. 2. Mount Lamington in 1947, looking eastward (by courtesy of R.A.A.F.).

Fig. 3. Mount Lamington cone, 30.1.51. Looking up avalanche valley into open northern side of crater.

Fig. 4. Vertical photograph of Lamington crater, 15 Nov., 1953.



Old dome remnant forms
southern crater wall
South eastern notch
Crater ring
Crater rim
Ancient
crater wall
New
lava dome
summit
Old dome remnant forms
present crater wall
Talus apron
North western
flows
Avalanche Valley
Western
"Avalanche
Valley" lava
flow
Coulée
Dolerite dyke in
upper Ambogo Valley

Note: In the original Bulletin, Figure 4 has a transparent overlay. If you wish to view the original, please contact the N.H. (Doc) Fisher Geoscience Library.

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Fig. 5. Columnar lava flow in western wall of avalanche valley, 11.2.51.

Fig. 6. Dyke intruding ejecta in lower end of avalanche valley.

Fig. 7. Chaotic deposits of upper cone exposed in gorge of upper Ambogo River.

Fig. 8. The native is standing on a residual of the March nuée deposit: his shoulders mark the top of an ancient nuée deposit exposed in the wall of the Ambogo Valley near the Coffee Mill.

Fig. 9. Nuée deposit: massive bed of small lava fragments covering old erosional surface. Exposure about 12 feet thick.

Farther down the slope, near the Andemba coffee mill, about 7 miles from the crater, other interesting sections are revealed in the Ambogo banks, where undercutting has produced vertical walls more than 100 feet high (fig. 9). At the base of the wall is a 30-40-ft. bed of unsorted fragmental material which is almost identical with that of the nuée material from the present eruption. The even surface of this bed slopes away from the crater, and it is overlain by crudely bedded agglomerates and tuffs which are predominantly of fluviatile origin. An old nuée deposit has apparently been preserved by over-riding mudflows that have sealed it against erosion. About half a mile farther down the river a similar unsorted bed of agglomerates is exposed in a cliff section. Here all doubt concerning its origin as a nuée ardente deposit is removed by a basal exposure which has characteristics similar to those obtaining at the base of the ashflows of the present eruption. An old erosional surface is covered by a thin bed of tuff which grades up from a grey sand to a fine dust. The sandy base contains abundant plant fragments, and the finer material above it is amassed into innumerable pisolites. Above the tuff bed the texture changes abruptly into unsorted angular fragments of the thick over-riding deposit. The close similarity between the basal characteristics of the ancient and the most recent nuée deposits strongly suggests that the characteristics of the earlier eruption have been repeated in the recent eruption; namely, an early climactic outburst of widespread destructiveness, followed, in the later stages of its activity, by extensive ashflows. The absence of very large blocks in these particular earlier deposits may indicate that a dome was not developed at the time of this eruption.

Cliff sections near the Popondetta airstrip, 11½ miles from the crater, exhibit a well-defined laminar bedding. Even this distance from the crater is not beyond the range of the chaotic deposits from the mudflows descending the mountain slopes, for some of the mudflows of the present eruption remained viscous and heavily laden well beyond this point. A shaft sunk at Popondetta, 13 miles from the crater, entered a bed of coarse unsorted fragmental material a few feet below the fine-grained tuff of the surface. This material was indistinguishable from deposits of the present eruption.

To sum up, then, the tuffs and agglomerates are typically chaotic deposits on the upper part of the cone, and well bedded deposits only become common on the lower gentler slopes of the mountain. The occurrence of earlier Pelean-type eruptions is indicated by exposures of deeply buried massive beds of unsorted agglomerate which have characteristics almost identical with those of the present eruption. Furthermore, the earlier eruptions may have had the same pattern of explosive release as that of the present eruption.

A measure of the antiquity of the deposits in the base of the Ambogo valley is probably indicated by the age determinations on a carbonized wood sample collected by S. J. Paterson from a deposit on the base of the comparable Embara valley. The altitude at the point of collection was about 2,000 feet and the approximate location is indicated on the map (fig. 52). The age has been determined by Fergusson and Rafter (1953) as 13,000 ± 500 years.

DRAINAGE.

The volcano is drained by radially distributed streams which are small but subject to sudden floodings. The streams are commonly entrenched 100 to 200 feet in the cone slopes, and many of the larger ones have a canyon-like valley profile, vertical sides, and flat, boulder-strewn bottoms. The Mamama River collects water from the radial streams of the rugged southern slopes and carries it west to the Kumusi

River, which receives also the individual streams from the western slopes. The Girua River functions similarly as a collector of the water from streams on the eastern flank of the volcano and carries the water east to shallow coastal swamps. Many streams of the unconfined northern slopes, including the Ambogo, end in meandering courses and shallow swamps on the coastal plain.

The Embi lakes on the northern slopes of the Hydrographer Range occupy valleys which have possibly been dammed by early mudflows from the slopes of Lamington.

SETTLEMENT.

Before eruption Mount Lamington was covered by heavy rain-forest and small scattered patches of cultivation. The fertile volcanic soils had attracted a much denser native population than is usual in Papua because their high fertility involved less work for these forest-dwelling people, whose usual agricultural practice was one of "shifting cultivation". Villages were numerous on the smooth northern and western slopes, and among them the Administration had established headquarters for the Northern Division at Higaturu, 6 miles north of the unrecognized crater and about 1,300 feet above sea level. Below Higaturu, about a mile to the south, Sangara Mission had its headquarters and school.

It is important to emphasize that before activity began Europeans and natives were all unaware that they were living on the slopes of a volcano. Neither history nor legend recorded previous activity from this centre.

PRELIMINARY PHENOMENA.

A popular misconception is that the catastrophic eruption of Sunday, 21st January 1951, occurred without warning. The first signs of the coming event were noted at least six days before but local people did not generally associate the initial observations with the beginning of an eruption. Owing to poor visibility, many people in the area did not become aware, until Friday, that an eruption had begun, and even then confusion existed as to the location of the activity. On Friday morning a radio message, originating from Awala, stated "Volcanic eruption seen 9 p.m. last night vicinity Tufi, intermittent flashes and discharge with billowing cloud apparently continued through the night, slight tremors felt during last 72 hours, rumbling heard locally, cloud effect still present; local weather perfect". Awala is on the north-west slope of the volcano, about 10 miles from the crater; Tufi is 80 miles east-south-east of Awala on the north coast.

Evidence supplied by local residents suggests that the early development of the eruption occurred in two phases: firstly, three days of slowly increasing gas emission, and secondly, three days of rapidly increasing activity which culminated in the great explosion. The late Miss Margaret de Bibra, principal of the Martyr's School at Sangara Mission, summarized the early stages of the eruption just before her death on the Sunday morning:

"For days we had earth tremors, at first occasional ones such as were experienced before, and then they became almost continuous and the face of Lamington became scarred with great patches of bare earth, caused by landslides. Then one morning, 18th January, after a night of continuous tremors, smoke appeared. At first there was only a little. Then it came pouring out in great thick puffs high into the sky, wreathing and curling in awe-inspiring cauliflower shapes. The first day there seemed to be only one crater, but on the next there were more, and on the third day, four or five, apparently in the area of the original crater, inside the circle of peaks. Early each morning the mountain was visible, and as the day went on more changes occurred; ash covered the peaks like a sprinkling of snow, the burnt patches of trees stretched further down the slopes, and the burnt earth areas were extending. Sometimes the column of smoke rose swiftly in the sky; sometimes there were flashes of fire; sometimes there were bursts of steam, but most of the day the whole mountain was covered in cloud and only the tip of the smoke could be seen, but deep rumblings could be heard, though tremors had ceased, and sometimes the air was heavy with sulphur fumes and later became thick with dust. We are fortunate that the prevailing winds do not come from that direction ".

This very excellent outline may be supplemented with observations from other people in the district to build a more detailed picture of the early events.

ACTIVITY BEGINS.

On Monday, 15th January, several people at Sangara Plantation saw, on the inner faces of the central peaks of Mount Lamington, landslides which appeared as brown streaks in the forest of the steep slopes. They were claimed by one person to have been evident several weeks before. These landslides were probably due to small localized earthquakes in the crater area. Occasional small tremors had been felt in the area during the previous few days, but they were not noticed by many people. The ground around the crater was becoming hot, too, for at 1500 hours a native cook at Sangara Plantation drew Mrs. Henderson's attention to a thin column of smoke which was rising from the base of the Lamington Peaks. When the native suggested that the smoke was a bad omen he was not believed, as at this stage the vapour column was very like smoke from a camp fire. However, the native, who came from the Tufi area, had apparently witnessed the 1943 eruption of Goropu volcano; hence it was not unexpected that he saw something ominous in this sign. The summit of the mountain was concealed by cloud later in the afternoon and a severe thunderstorm occurred that night.

On Tuesday activity increased slightly and the vapour column was seen for the first time from Higaturu. More extensive landslides moved down the slopes of the inner peaks, and Mr. Gwilt, observing from Sangara Plantation, reported that much of the vegetation had been removed from the inner slopes by late afternoon. At 1600 hours a mild earthquake felt at Higaturu marked the beginning of the swarm-pattern earthquakes which became widely felt throughout the area. The District Commissioner's wife, Mrs. Cowley, counted 30 shocks at Higaturu during the next twelve hours. More powerful shocks were felt near Issivita, north-west of the crater, where the movement was described as the " whole earth rocking "; slighter shocks were felt at Sangara and Waseta.

When the mountain became visible at 1030 hours the next day, a steady stream of vapour, together with a little ash, was ascending to a great height. The activity increased in volume and density during the day, and earthquakes occurred with monotonous regularity in the surrounding area. At Higaturu, Patrol Officer James reported that shocks were occurring at seven-minute intervals. At Sangara Plantation they were less frequent, but very consistent. No luminous effects accompanied the activity that night.

THE MORE ACTIVE PHASE.

Thursday revealed a marked increase in activity and many people became aware of the eruption for the first time. The emission rate increased throughout the day, and by nightfall the smoke was described as " gushing forth at a great rate ". The quality and character of the emission had both changed; now the smoke varied in colour from black to grey and spasms were noted in the crater activity.

Mr. James observed: " Rumbling could be heard both before the eruption and afterwards, but I think it was only the sound of landslides, which must have been colossal as they took whole trees and jungle and left the slopes bare and earth-covered. There was a flow of something in one of the ravines, but we are unable to make out whether it is water, lava or earth."

More distant observers described the emission as a slow-moving, continuous dark-grey column ascending to many thousands of feet.

In the early hours of the morning, when the crater was concealed by cloud, the District Commissioner and his wife heard a roaring from the mountain. Later, when visibility cleared, they made an interesting observation by means of a telescope which had been set up outside the house. Mrs. Cowley said: " By midday . . . a large hill had built itself up between the hills at the foot of Lamington and the mountains at the rear. It was from the top of this hill that the ash was now issuing in terrific force, and flowing over the sides was a steamy white cloud which we could not distinguish even with a telescope, but it did not come more than about a third of the way down the newly built hill." Considerable quantities of ash had begun to fall close to the crater, for the telescope revealed also that the forest on the eastern side of the crater was stripped of leaves and branches.

" That night," observed Mr. Gwilt, " in clear moonlit sky, flashes of light, more brilliant than lighting, were visible intermittently in this vast column, with noises which sounded like thunder; up to this point there did not seem to be any subterranean rumblings. . . ." Mr. Henderson, also at Sangara Plantation, saw cone-shaped flashes in the cloud column above. At 0130 hours Father Porter at Issivita was awakened by the noise of thunder. Vertical flashes of lightning were seen at the summit of the mountain and " the whole sky was alive with electrical activity ".

Earthquakes became more numerous on Thursday, and by midday they were described as " almost incessant " at Higaturu. A party of native police which went towards the crater in the morning returned at noon because the ground was shaking so much. Tremor swarms were also being felt at Issivita and Waseta and many people in Higaturu were becoming alarmed; some found sleep difficult owing to the earthquakes.

On Friday morning a light coloured ash lay like snow on the summit peaks of Lamington. The spasms in the crater emission had become more pronounced and they could now be seen from Sangara Plantation. The eruption cloud had now become visible for the first time to people in the Waseta and Kokoda areas, and to some of them this constituted their first knowledge of the eruption. At 1500 hours Mr. Kienzle at Yodda Valley, near Kokoda, about 35 miles west of the volcano, saw a black cloud " issuing out at a fast rate but not reaching higher than 15,000 feet ". Activity must have fluctuated during the day, because at midday Judge Phillips examined the volcano and reported a continuous column of light-coloured vapour ascending to 20,000 or 25,000 feet. The emission was continuous and no violent movement was perceptible in the column. A thin layer of cloud covered the summit of the mountain and concealed the vents from which the vapour was originating. From the description given to me it seems highly probable that activity was confined to the southern vent, which became a notable point of gas emission during the subsequent stages of the eruption.

From Sangara, however, Mr. Gwilt gives us a different picture of the activity: "This day (Friday) definite subterranean grumblings were heard. Until now, the column had risen in a uniform pattern, except when wind was evident; immediately after a rumble it was evident that smoke belched from the crater and it would then conform to pattern; this procedure continued all day and night."

From Waseta, in the morning, Miss Marie Reay, who was engaged on anthropological research in the area, saw a great column of smoke rising from the direction of Issivita and made a note in her diary to the effect that Mount Lamington had erupted for the first time in recorded history. She found the natives had no knowledge, or legend, of an earlier eruption. Later in the day she spoke to a number of people who had come from the Issivita area. They told her that stones were falling on their gardens and the earthquakes were very severe. Some houses had collapsed, and during the night people hung on to ropes fastened to trees in order to keep themselves from being thrown about by earth tremors.

At 1530 hours Miss Reay noticed " the smoke was dispersed over a great area of sky and was swirling very high ". That night the stench of the volcano was unbearable; her description of the " stench " suggests a mixture of sulphuretted hydrogen and sulphur dioxide. The night was windless and the crater cloud ascended once again in a great column. The active centres shot " great leaping sparks in to the smoke [column] which in the darkness is a little paler than the trees and looks like black fudge ".

As heavy rain fell at Issivita that night the mountain was probably clouded in for most of the evening, which would explain why only one other observer mentions having seen luminous effects in the ascending column that night.

Saturday was a clear day and many observations of the greatly increased activity were possible. New vents had opened in the crater and, in the ash-laden cloud, brilliant luminous effects were observed. From Kokoda, in the morning, Mr. Yeoman saw a column which " had the appearance of a black wall with a straight face towards the sea, turning over at the top of the wall and back towards the Managalasi area. Behind the face and beneath the bent-over column of smoke the sky was black, like black night. Through the field glasses the billowing smoke had something of the appearance of a cauliflower and was similar to an oil fire. The smoke was illuminated from within by huge, curved red flashes of light."

Further up the valley at Yodda the column was visible all day and the unvarying nature of the activity throughout the day was emphasized by Mr. Kienzle. " Fresh bursts of energy " pushed new material up into the " practically continuous stream " at intervals of three to five minutes and a wind at about 25,000 feet carried the top of the column towards the south. At night extraordinary luminous effects were again observed. " That evening we were able to see what appeared to be fireballs bursting in the mass of the clouds above 10,000 feet. These were not visible as long streaks of flame but only as short tails immediately prior to bursting in a dull red glow. Definitely not to be confused with lightning."

The most significant observation made by people close to the volcano was of an extension of the active area in the crater. Miss de Bibra observed " four or five craters " whereas originally there had been only one and Father Porter's observations seem to confirm Miss de Bibra's when he says: " The crater now seemed to be much more on our side and though I could not be entirely certain, it did appear that we could actually see the smoke from the ground and dead trees were visible in the near vicinity ". Evidently vents on the western side of the crater had opened up.

Father Porter also makes an interesting observation on the quality of the emission at that time: " The smoke was much denser than before, and, indeed, was hardly like smoke at all. It was just a grey mass which seemed to curl out of the ground like tooth paste squeezed from a tube ".

The people in the Issivita area were terrified and some from the villages of Hamumutu Pinja and Popandota, which were closest to the crater, moved out.

The sound effects from the crater had been increasing greatly over the last two days. Mr. R. Hart, at Jegerata village, about ten miles from the crater on the north-eastern slopes of the mountain, compared the sounds to a gigantic underground railway. Jegerata is, in effect, opposite the open north face of the crater and there are no deflecting obstructions between it and the crater, which may account for the fact that sound effects were not so loud elsewhere. Even so, the sounds were more pronounced everywhere on Saturday and it was said the rumbling was not unlike the very rapid boiling of a pot. It was as if the noise were composed of a rapid succession of separate explosions blended into a continuous pattern of sound. Similar effects were noted at St. Vincent, in 1902, where such sounds were compared to the rattling of an anchor chain or a carriage over cobblestone.

Spasmodic rumbling was heard at Issivita all that night.

From Sangara after nightfall electrical and luminous effects were seen in the rising column. " That night . . . a new phenomenon appeared in the shape of whirling stars reaching the full length of the column, intermittently mixed with brilliant flashes of light; these whirling stars gave the impression that they were seen as through a dense fog ". The " whirling stars " may have been due to the not uncommon volcanic phenomenon of stellar lightning rather than to incandescent material, but it is hard to say, because at a distance the effects appear similar. However, from Waseta, Mr. Morris noted " horizontal flashes " which suggest short bars of stellar lightning. " Flaring patches of blue light " were also noticed emanating from the crater; this phenomenon was compared to the spasm of flame seen when a gas jet back-fires.

The earthquake swarms appear to have continued during this day with much the same frequency as on Friday. They receive small mention in the accounts of local observers, however, as by that time they were taken for granted. They must have been very numerous at Sangara Plantation during the day, because Mr. Henderson noticed that they stopped at 2000 hours. Occasional shocks were felt later that night.

No great change in the activity of the crater was apparent early on Sunday morning. The column was blacker and looked as though it contained more ash; otherwise the intensity of emission had not increased.

Later in the morning, however, the intervals between the rumblings and their following belches of smoke became shorter. At 1000 hours Mrs. Stephens at Sangara Plantation observed " a small area to the left (of the crater) and much lower on the slopes burst forth into cloud and smoke ".

At 1020 hours, according to Mr. Gwilt " the activity had greatly increased, the Lamingtons now being practically obliterated by violent belchings of smoke ". Shortly afterwards wireless reception became a roar of static and the great explosion had begun.

SUMMARY AND CONCLUSIONS.

The events leading up to the climactic eruptions began with occasional slight earthquakes which were felt by few people living within ten miles of the crater. Many people noted landslides around the crater on Monday, 15th January, and on the same day a short glimpse was seen of a thin column of vapour rising from the mountain. This gas emission increased slowly on Tuesday and Wednesday, and at the same time earthquake swarms became widely felt in the settlements surrounding the volcano.

A phase of rapid increase began on Thursday. The gas emission became loaded with ash and its nature changed to a rhythmic pattern of pulses or " belches " which produced a continuous column rising to many thousands of feet. On Friday and Saturday the pulses became stronger and more frequent. Definite subterranean sounds accompanied this development and the noises increased with the growing magnitude of the emission. At the same time volcanic earthquakes had become so numerous that they were described as " almost incessant " at Higaturu, about 6 miles north of the crater.

At 0130 hours on Friday morning extraordinary electrical phenomena around the mountain were observed from Issivita. The next morning ash covered the summit of the mountain, and it seems likely that, during this preliminary stage of more or less continuous gas emission, powerful spasms of activity occurred. Whether this activity produced minor nuées or ash flows is problematical. Observers in Higaturu saw a flow of " water, lava, or earth " in one of the ravines on Thursday which could have been landslide material; the description is not sufficiently specific to definitely attribute it to another cause. Unlike the prototypes at Pelée or St. Vincent, Mount Lamington had no crater lake to expel, so the flow cannot be attributed to that cause. Most probably, it was a mudflow caused by damming of the drainage by landslides.

The most promising evidence that some form of nuée was produced before the climactic explosion is Mrs. Stephens's observation, on Sunday morning, of an area low on the north-eastern slopes " bursting forth into cloud and smoke ". Such activity seems typical of the cloud expanding from a small preliminary glowing cloud. Similar precursory events at the West Indian volcanoes were confused with external vents. Therefore it seems probable that, although the preliminary activity was essentially normal vulcanian in character, close observation would have seen evidence to suggest a sudden change to a Pelean outburst.

There is little evidence to suggest a dome in the crater during this early activity. Mrs. Cowley's observation that a hill had been built in the crater indicated rather a cone of fragmental material around the southern vent than a dome, because eruptive material was emerging with great force from the summit of this structure. A terminal vent in a dome is the exception rather than the rule, especially with an obviously powerful vent such as this.

The more vigorous phase of the preliminary activity produced brilliant electrical phenomena with chain, bar, stellar, and sheet lightning, and in addition other luminous effects were observed which may have been due to incandescent lava. The red flashes and fireballs which burst with a dull red glow could be attributed to the bursting of volcanic bombs; but similar red flashes observed in 1902 at St. Vincent were attributed to an electrical origin (Anderson and Flett, 1903, p. 407). Some observers also saw blue flashes coming from the crater; these were variously described as " flaring patches of blue light " and " tongues of flame ". Whether this phenomenon was due to burning gases is open to doubt: I saw similar effects in a later eruption and attributed them to an electrical phenomenon.

During the day before the great explosion a continuous column of ash ascended to at least 25,000 feet; one observer estimated it at 30,000 feet. This activity was certainly a major development: at few times during the activity that followed was ash ejected to such a height. Had the prevailing wind brought this material over the settled areas of the northern or western slopes Lamington might have had a different story: undoubtedly many people would have moved away from the mountain as they did from the western side of St. Vincent in 1902.

The most important visible indications of the approaching explosion appear to have been the daily extension of the active areas within the crater and the shortening of the intervals between the rhythmic sub-explosive pulses of activity which produced the towering column of ash. Even during the half hour before the explosion a marked increase in this activity was observed.

An attempt to outline this preliminary activity by a graphical summary has been made (see figs. 13 to 20). Special features of the seismic activity are discussed under that heading.

THE CLIMACTIC EXPLOSIONS.

At 1040 hours on Sunday, 21st January, the volcano produced an explosion of great magnitude. A large mass of ash was projected rapidly into the stratosphere to form a huge expanding mushroom-shaped cloud. The base of the column began to expand laterally as clouds of incandescent ash swept down the slopes of the mountain and laid waste more than 90 square miles of country.

The eruption was uniquely observed and photographed by the occupants of a Douglas aircraft which was on the normal QANTAS flight from Port Moresby to Rabaul. The aircraft was flying at 9,500 feet and the course was 040° from Port Moresby. An odour of sulphuretted hydrogen was very noticeable over the Kokoda Pass in the Owen Stanley Range, and Captain Jacobson veered slightly off course as the volcano was approached in order to have a better view of activity. A seven-eighths layer of cumulus cloud at about 3,000 feet partly obscured the base of the cone. A continuous column of black ash rose from the crater and, penetrating a seven-eighths layer of nimbo-stratus cloud at 14,000 feet, expanded greatly above it. The column appeared to be perfectly flat on the north-eastern, or windward side and relatively narrow until it reached 14,000 feet.

When about 25 miles north-west of the volcano, at 1040 hours, Captain Jacobson saw a dark mass of ash shoot up from the crater and rise, within two minutes, to 40,000 feet, forming a huge expanding mushroom-shaped summit (fig. 10). The base of the column expanded rapidly as if the " whole countryside were erupting " (fig. 11).

Captain Jacobson left the area at 180 knots. Twenty minutes later, from 4,000 feet, he saw that the expanding mushroom head of the eruption cloud had passed over the aircraft at about 50,000 feet. It was undoubtedly composed of fine ash and

[To face page 24.]

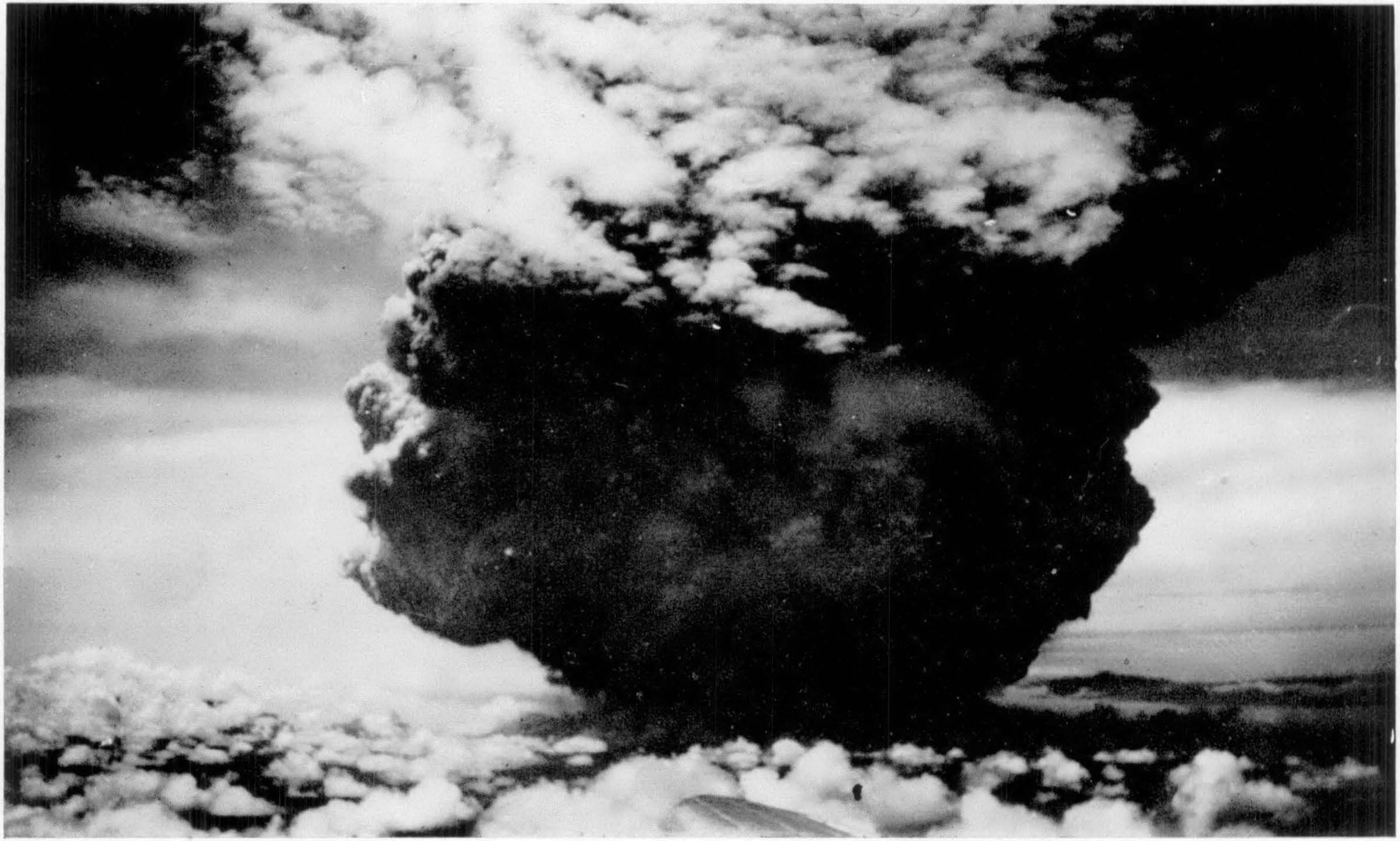

Fig. 10. Climactic eruption, 21.1.51. (By courtesy of Capt. Jacobson.)

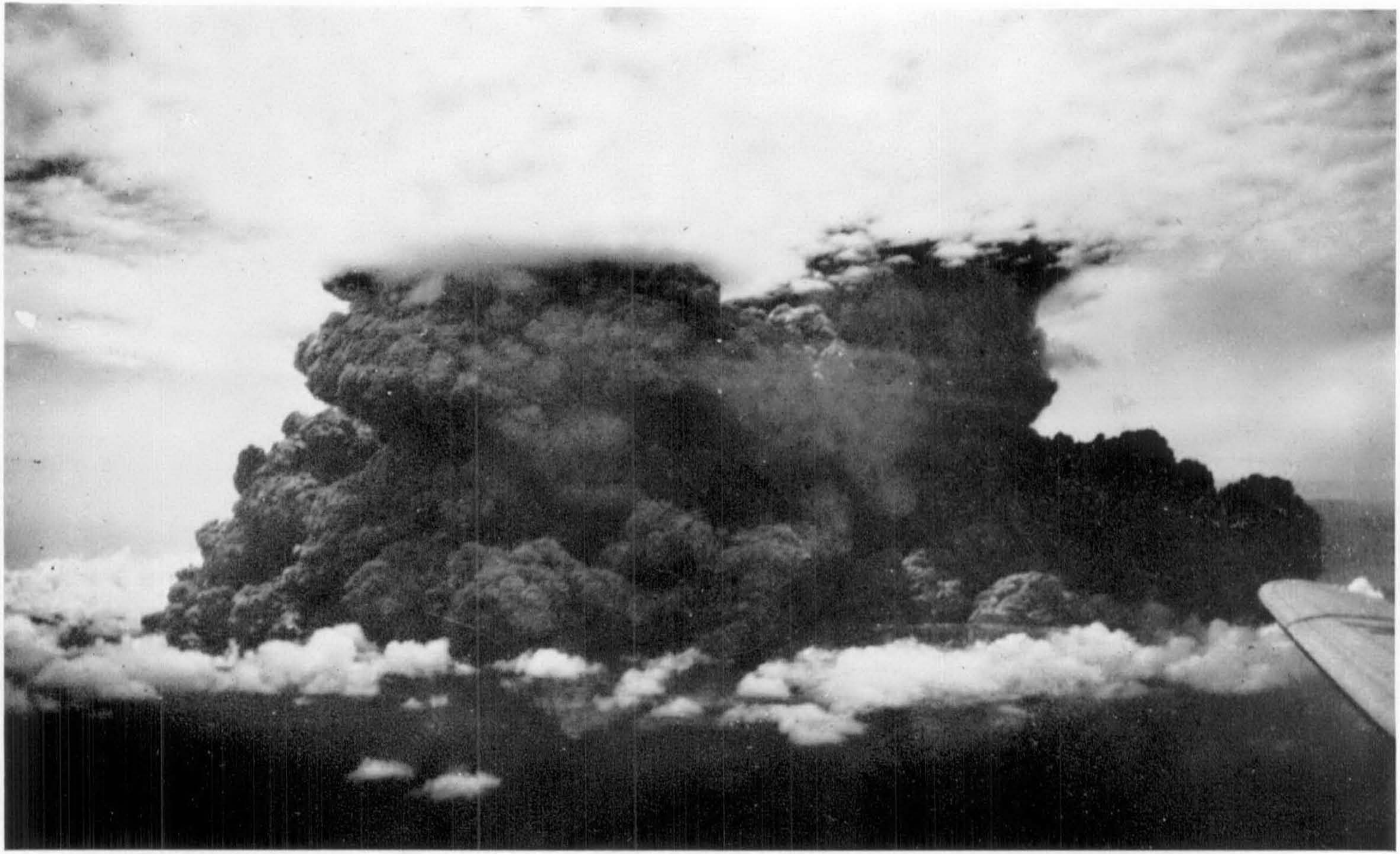

Fig. 11. Climactic eruption, 21.1.51. Ash clouds are rising from avalanches to the right. (By courtesy of Capt. Jacobson.)

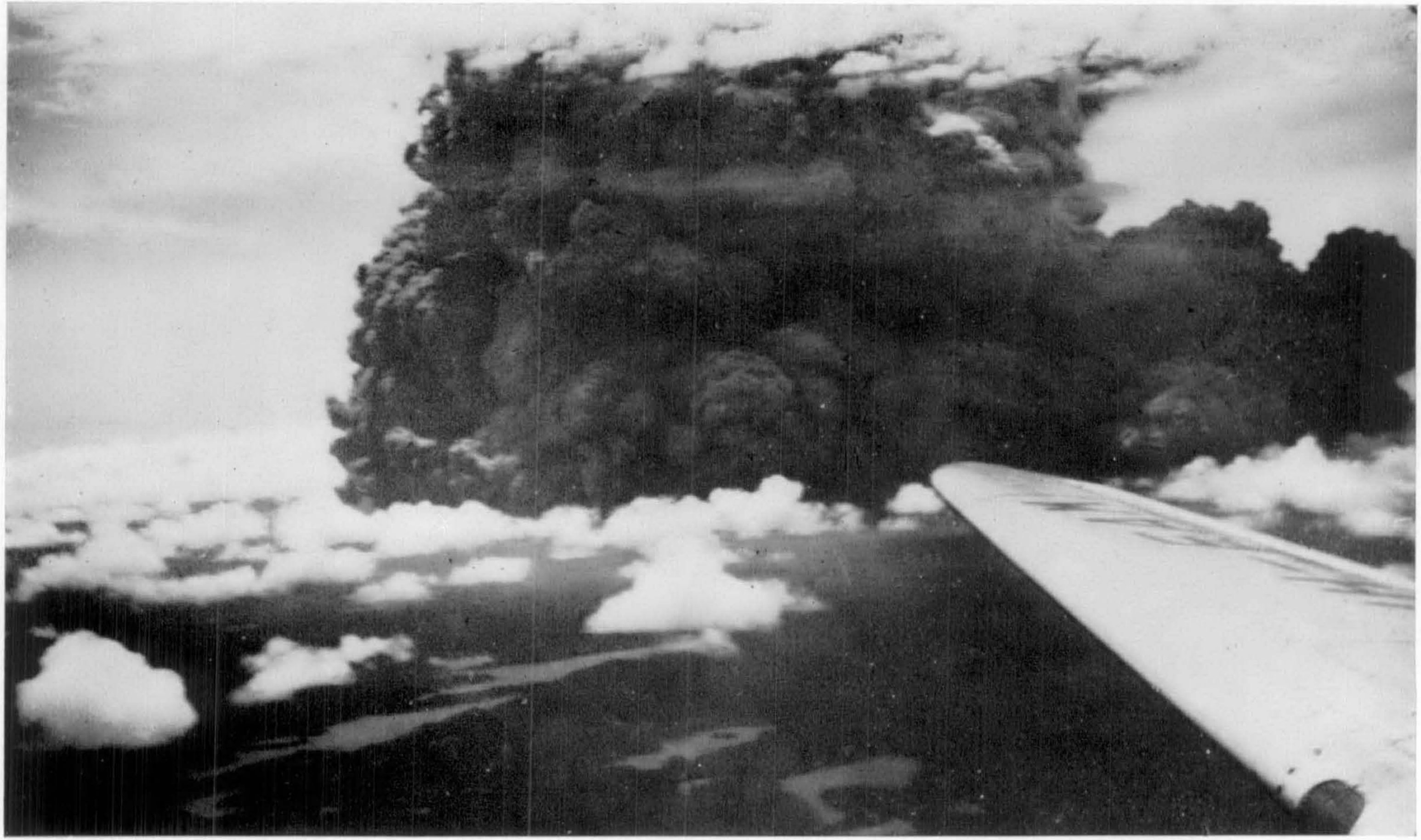

Fig. 12. Climactic eruption, 21.1.51: the ash clouds are increasing. (By courtesy of Capt. Jacobson.)

gas; the aircraft was unaffected. From well out to sea; the dark eruption cloud appeared to have enveloped an enormous area of country, many miles in diameter. The cloud was still visible from Gasmata, 250 miles to the north-east, on the south coast of New Britain.

This tremendous release of energy was awe-inspiring and terrifying to the people living on the slopes of the volcano, and almost immediately large numbers began to flee. Such was the velocity of the enveloping cloud, however, that only those on the extreme edge of the subsequently devastated area were able to escape.

Sound Effects.

For many people the first indication of the explosion was a change in the sounds from the crater. At Issivita the " irregular rumblings gave way to a long continuous even roar which increased in volume but did not become deafening. I should say this roar lasted from three to four minutes. Our next observation was that a dense grey mass was moving swiftly towards us at ground level from the Higaturu-Sangara side of the mountain."* At Jegerata and Sangara plantation the continuous roar was also heard. Some residents reported that they heard an explosion, others that they heard a series of explosions. From the more distant centres of Popondetta and Waseta the noise was described as a prolonged loud rumbling which resembled thunder. One observer reported a long narrow flash of lightning followed by complete silence.

The dominant sound in this explosion appears to have been the prolonged roaring noise associated with the release of enormous quantities of gas. The outbursts heard close to the mountain do not appear to have been very loud, and 13 miles from the mountain they were only heard as rumbling; that the noise was heard also at Kandrian, 200 miles distant on the south coast of New Britain, is a not uncommon anomaly. No concussion effects were reported.

The Lateral Cloud.

An eye-witness of the outburst of Mount Pelée on 8th May, 1902 said that at the moment of eruption the mountain appeared to split in two; others claimed that a black cloud emerged from below the crater. A similar effect was produced at Lamington, for it appeared to observers who were able to see the crater that the whole mountain was disintegrating.

The reason for this can be seen partly in photographs taken from the aircraft (figs. 10, 11 and 12). Avalanches of material swept down the slopes of the cone and almost simultaneously the gas, expanding from these avalanches, formed a huge vertically rising, seething cloud of ash which gave the illusion that active centres were extending to include the whole mountain.

At Sangara, as preparations were being made to flee, the black cloud " whirling and billowing like an oil fire " could be seen advancing towards the Plantation with an incredible appearance of solidity. The summit of the cloud appeared to curl over like a wave about to break on shore, but when its front was less than a mile away a brisk breeze sprang up and the cloud rolled back again. Overhead, and extending almost to the horizon, the heavens were concealed by an enormous umbrella of ash. A few minutes later ash began to fall and as the party proceeded down the road to Popondetta it was subjected to a rain of mud which later, as Popondetta was approached, changed to dry pisolitic ash.

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* Father Porter.

At Issivita the cloud advanced half way across the Mission station before a sudden wind swept it back. A 2 inch layer of fine light-grey dust marked its sharply defined limit. Ten to fifteen minutes later, at approximately 1055 hours, wet mud began to fall, followed by a fall of sand and small stones. Five minutes after this second fall began complete darkness descended and lasted until 1230 hours, after which visibility gradually returned. During the remainder of the day, light in this dust-enshrouded area was similar to the early morning light before sunrise on a normal day.

The crater, meanwhile, was concealed by the dust haze which hung over the area. Deep-seated rumblings throughout the afternoon were ominous, and from nightfall onwards the rumblings became louder and more frequent.

The Night Eruption.

Wireless schedule with Port Moresby, arranged by Mr. Searl of Awala Plantation for 2045 hours, could not be kept as a second violent eruption caused an electrical disturbance which made transmission impossible. When this second outburst occurred, the last truck had just left Sangara Plantation for Popondetta, and Mr. Gwilt, sitting in the back of it, had a full view of the eruption as the vehicle moved northwards:

". . . the eruption was plainly visible in the bright moonlight . . . the column was now racing towards us from behind; ahead and above us was the moon. Watching with fear that we would be overtaken, I kept a constant watch on the column which appeared to be infinitely wider than the previous one in the morning, I heard nothing but saw everything, including a dull red half circle of what appeared to be a blood red moon shape stationary over what I considered to be the direction of the crater. This moon-shaped light was penetrating and visible as seen through dense smoke, quite defined but blurred. This was visible on numerous occasions as we climbed from lower to higher ground. Shortly after, a wind blowing approximately from south-south-east, and at a height of several thousand feet, with a velocity which could not be gauged, was forcing the canopy above us in the direction of the moon. During this period there appeared to be no scintillating lights visible in the column to the south, but overhead as the smoke canopy was approaching the moon, these scintillating lights were apparent. By this time the canopy of smoke was obliterating the moon at an angle of 45° ahead of us, from the zenith. Some minutes after the moon was covered by the canopy, a wind arose approximately north-north-west, again checking and rolling back this vast canopy with the column of smoke still well behind us. On reaching Popondetta on this trip we experienced no fall of pumice. The wind had folded the canopy again for the second time that day towards Mt. Lamington; we arrived in moonlight."

These observations indicate that the night eruption was of a different type from that of the morning: had there been a nuée ardente its dense clouds would have concealed the glow of incandescent material from the crater. Further, Mr. Stephen's observation of the eruption from a point midway between Popondetta and the coast confirms the view that the eruption was a vertical projection of normal vulcanian type. From here, too, the noise of the explosions could be plainly heard and the shape of the column was visible in the moonlight.

The observer closest to the volcano, Father Porter at Issivita, has reported:

"The second eruption occurred at about 9.30 p.m. We knew it was coming because of the familiar even roar which had preceded the morning blast. This time we seemed to hear sharp cracking noises just above the roof, similar to fireworks exploding. Then the fall began. Much larger stones fell among the sand. I should say it went on for twenty minutes. Being night time it was difficult to observe the visibility but I should say it was about the same as the morning. After the second eruption the mountain was completely silent except for a few slight rumbles in the morning."

Father Porter's observations confirm the importance of the rumblings in the crater as an indication of the unsettled condition of the volcano.. None of the observers makes reference to the occurrence of earth tremors during this period.

To the west, at Waseta, Mr. Morris made more detailed observations on the ejecta and the magnitude of the eruptions; " That night, I do not know the time but it must have been about 9 p.m., I was driving a tractor in low gear towards Awala and heard above the considerable noise of the engine, a heavier rumble from the direction of Issivita. I drove for cover at top speed but before I could go more than 100 yards, stones began to fall, but so sparsely that I had almost reached shelter, another 200 yards, before any hit me. The stones were about the size of a walnut with a few larger and many smaller. They were of a crystalline nature, very much like granite in appearance and appeared to have been fused by heat. Some were flat on the base and honey-combed, others were irregular, but all were very light in weight.

" These stones fell more thickly as they reduced in size and I heard a loud noise as of approaching heavy rain coming towards Waseta from Issivita. The sky was in the sky. The noises heard were very much greater than those of the morning very loud and a dense deposit of crystalline ash fell. I tested this from time to time to see if it was hot, but it was quite cool. I do not know how long this lasted but would guess about three-quarters of an hour. During the last of this fall I drove back to Waseta. I was not troubled by dust; this second fall seemed to have none of the fine dust of the first deposit.

" The night eruption was very much heavier than the first blast. It seemed so strong and close to Issivita that I was certain it had been wiped out ".

From the Kokoda area the eruption was seen to begin about 9 p.m. with rumbling and lightning from the direction of the volcano, and once again with fireballs bursting in the sky. The noises heard were very much greater than those of the morning eruption; some of them may have been caused by electrical effects in the dust clouds drifting over the valley. A heavy fall of ash occurred at Kokoda. Activity ceased at 2300 hours. Mr. Kienzle made the curious observation that the heaviest fall of ash occurred at Yodda at 0200 hours, which is some hours after this activity had ceased. This hour corresponds with a roaring noise heard by Sister Durdan at Issivita. Although no ash fell here, it is certain that another, less noisy, outburst took place at this time.

THE PATTERN OF ACTIVITY.

Perret (1937) observed that certain long-dormant volcanoes of the closed conduit type produced eruptions which had three consecutive but overlapping phases, namely: a phase of violent explosive activity, a phase of moderate activity, and a phase of quiet extrusive activity.

He believed this pattern of behaviour to be due to the distribution of higher gas concentrations in the upper part of the magma column, and used this hypothesis effectively in diagnosing the condition of Mont Pelée in 1930. The activity pattern of Lamington is similar in many respects to that of Pelée, although the period of powerful explosions is shorter.

After the climactic explosions of 21st January, Mount Lamington remained quiet for three days. Explosive activity was resumed on 25th January and during the next six weeks spasmodic outbursts, some of considerable power, occurred. More notable explosions took place on 6th, 18th, 22nd and 24th February and on 5th March. The first week in March marked the end of the most powerful explosive phase and there were much longer periods of quiesence between the few milder outbursts which followed. After June the extrusive or dome-building phase, which had actually begun a few days after the climactic outbursts, became the main form of activity, and it continued intermittently for more than a year and a half.

THE PHASE OF HIGH-EXPLOSIVE ACTIVITY.

The high-explosive phase of the volcano's activity was concentrated into the comparatively short period of less than two months.* Other explosions occurred between early March and the end of June, but they contributed only minor quantities of ejectamenta to the earlier deposits. The longer periods of quiescence, suggesting a phase of declining power, place these explosions in a different category from that of the earlier activity.

Since the period of major explosions is of most concern to the vulcanologist, an attempt has been made to give a clear and comprehensive picture of the early activity by depicting graphically the observations of the first two months of the eruption (figs. 13 to 20). As many observations as are practicable have been entered. Gas emission, explosive or otherwise, is represented by bars and broken lines, the thickness of which represents an arbitrary estimate of magnitude; the length is a measure of the height of the ejected cloud. Whenever practical the heights were measured by clinometer or alidade, but it was often possible only to estimate heights. To depict the very large range in size and height of the explosive manifestations it has been necessary to show the climactic explosions as blocks rather than bars, and to draw both from sea level, although the section of the bars below the crater floor, which is represented by a broken line, is irrelevant. The graph is not a complete record but a representation of the scale and explosive activity taking place at a particular time. It includes almost all the major explosions and the main trends of the explosive activity in spite of the poor conditions of visibility. For the greater part of the time that the volcano was under observation the summit was concealed by cloud, and although the early mornings were usually clear it was rare for good visibility to last until mid-day; in the afternoons heavy cumulus cloud normally concealed everything above 3,000 feet.

Four days can be taken as peak periods of energy release. Major explosions occurred on 21st January, 6th and 18th February, and 5th March. The outbursts are separated by comparable periods of almost two weeks, and their magnitude, after the climactic explosions, progressively increases up to the eruption of 5th March, which marks a change in eruptive behaviour. The pattern of this activity has a broad periodicity which, combined with a later explosive sequence of rising power, suggests that we are dealing with a relatively homogeneous set of eruptive forces rather than a random series of events.

Detailed examination of the eruptive mode again reveals a uniformity in the processes of eruptions and, at the same time, changes in the pattern as the eruptive energy declines. The first two peak eruptions, on 21st January and 6th February, are repeated patterns in that they represent culminating points which follow periods

* Mont Pelée's paroxysmal activity, in 1902, lasted at least twice as long, and St. Vincent produced powerful explosions ten months after its initial activity.

of increasing explosive activity. The climactic explosions on 21st January followed a period which had a uniform pattern of consistently increasing activity; the later eruption, on the 6th February, had a comparatively irregular prelude of intermittent explosions which increased in magnitude after a new gas phase had been introduced by a series of larger explosions. These larger explosions, which occurred on 25th, 27th, and 28th January, ended the post-climax calm. They are a curious echo of the climactic release, for each is two explosions separated by twelve to fifteen hours of calm. A similar grouping of explosions into pairs is also characteristic of some of the later activity, and it is of interest to note that some of the larger explosions of Pelée and St. Vincent have complementary after-explosions (Anderson and Flett, 1903, p. 498), as if one gas phase triggers off another by changing a factor in the condition of magma equilibrium. The larger explosions introduced a gas phase with numerous small explosions, which, from 31st January, became interspersed with outbursts of very much greater power. Ash was projected to 12,000 feet, and the explosions increased in frequency until 6th February. At least two large explosions occurred daily two days before the activity culminated in a series of three powerful explosions which projected ash clouds to more than 24,000 feet between 1250 hours and 1330 hours on 6th February.

The two later major outbursts on 18th February and 5th March have a much briefer period of preliminary activity. In fact the eruption of the 18th is in some respects a complete reversal of pattern. If the mild build-up to the small eruption of 11th February is regarded as a faint echo of the previous eruptive pattern, then the large outburst of the 18th may be regarded as the abrupt beginning of a new gas phase. It was followed, on 22nd and 24th February, by powerful eruptions of declining intensity. The preliminary activity of the paroxysmal eruption of 5th March was almost indistinguishable from the declining activity which followed the February eruptions. Observations were made more difficult by the poor visibility which prevailed at this time. The complementary steam explosion which occurred on 7th March was seen only by observers at the Popondetta airstrip; low cloud concealed it from the Observation Post at Sangara. Most of the phase of declining explosive power went unobserved because of poor visibility during the following months.

TYPES OF EXPLOSION.

Classification of the types of explosions from volcanoes which produce glowing clouds is based essentially on the study of the eruption of Mont Pelée and St. Vincent by Lacroix (1904) and by Anderson and Flett (1903). Differences in the crater structures and the distributions of the glowing clouds lead to different interpretations of the mechanism of such eruptions. The Soufrière at St. Vincent had a high-walled symmetrical crater slightly lower on its southern side but without a deep breach or notch, and the great lateral cloud which devastated the slopes on 7th May, 1902, was distributed radially on all sides of the crater. A slightly heavier concentration of ejectamenta was evident on the side of the mountain below the lower southern rim. Anderson and Flett concluded that the phenomenon was a gravity-controlled avalanche of gas-emitting fragmental lava, and their observation of the Pelée eruption of 9th July did not alter this view. The Pelée crater differed from the Soufrière in that the crater wall contained a gap on the south-western side, and from an early stage of the activity a dome rose from the floor. The initial paroxysmal explosion produced a nuée ardente which devastated a fan-shaped area on the slopes below the gap in the crater wall, and most of the later nuées proceeded in the same general direction. In order to explain the intensity of the phenomena in the larger explosions of 1902—8th May, 20th May, and 30th August—Lacroix postulated that a directed explosion initiated the nuée ardente. This " nuée peléanne d'explosion dirigée " began with an oblique " cannon shot " which gave it impetus to attain extraordinary velocities of 150 metres per second and to carry large blocks across valleys. He recognized the importance of gravity in the lateral movements of the nuée, but unlike Anderson and Flett considered the lava to be solidified and to have formed an emulsion with the steam and hot gases. Decline in the power of the initial projection produced a series of lesser manifestations of the same common origin, from the " nuée ardente d'avalanche " to the gas-free avalanches of blocks from the dome flanks. Lacroix placed the nuée ardente which originated from a vertical explosion into an entirely different category, that of " nuées ardentes d'explosions vulcaniennes ".

Macgregor (1952) discusses some of the misconceptions which have arisen over the eruptive mechanisms of the glowing cloud type and summarizes the characteristics of Mt. Pelée and the Soufrière of St. Vincent as follows:—

" Nuée ardente eruptions at Mt. Pelée differed from those at the Soufrière because, at Mt Pelée, a dome was rising behind a deep crater-rim notch during the whole period of activity. During most of the eruptions the notch gave rise to, or coincided with, an area of relative weakness on the flank of the dome; behind the weak area originated explosions necessarily of a somewhat directional character. The explosions originated in dome magma that was not fully consolidated, and produced self-explosive (gas-generating) avalanches (nuées ardentes) of varying degrees of magnitude and initial energy; they carried lava fragments with a great range of size, including large blocks derived from the carapace of the dome. Gravity, as a rule, was by far the dominating factor in giving speed and momentum to the avalanches. The nuées ardentes at the Soufrière of St. Vincent were initiated by vertical explosion in a domeless crater, were distributed radially on the slopes of the volcano, and owed their speed and momentum entirely to gravity; the lava fragments in these nuées were finely comminuted. As at Mt. Pelée the mobility of the nuées was due to the self-explosive (gas-generating) properties of fragments of new lava. At the Soufrière these were produced by the minute explosive fragmentation of new, semi-crystallized magma in the conduit immediately below the open crater ".

Clearly, then, the dome is the important factor in determining the eruptive mechanism of these two volcanoes.

If nuées ardentes can be classified genetically, and not on some freakish disposition of vents, a volcano similar in structure and development to Mt. Pelée should exhibit like phenomena. Mt. Lamington is remarkably similar to Pelée in its crater structure and its dome formation. Both have crater walls which are breached on one side; the Lamington breach extends the full width of the crater on the northern side. Both developed lava domes early in the eruption; Pelée is said to have formed a lava dome before the catastrophic eruption of 8th May, and it appears from a study of air photographs of Mt. Lamington taken in 1947 that a small dome existed here also before activity began. It is likely that the " hill " in the crater seen by observers during the preliminary activity was this dome with the vegetation removed, giving the illusion of the development of a new structure. The climactic explosions apparently destroyed this dome and reamed out a considerable portion of the old southern and south-eastern crater walls. The post-eruption crater is more symmetrical than that which existed beforehand. In less than three weeks after the climactic explosions a dome had been extruded 1,000 feet above the floor of the Lamington crater. In spite of these resemblances a close study of the eruptive phenomena suggests that the explosive activity of Lamington has more affinity with the domeless St. Vincent volcano than with Mt. Pelée, and that the type of explosion is related to the physical condition of the lava and the number of gas phases operating rather than the presence or absence of a dome.

One factor common to volcanoes which produce laterally moving clouds of incandescent ash is the occurrence of normal vulcanian explosions during the course of their eruptions. Even the classical paroxysms of Pelée on 8th May, 20th May and 20th August, which Lacroix (1930) considered to have produced examples of a directed oblique or horizontal explosion, projected ash to great heights and covered hundreds of square miles with ejectamenta. Similarly, in the lesser eruptions of 26th May, 6th June, and 9th July, powerful vertical projection was always evident, and some of the minor outbursts of intervening periods were purely vulcanian. A similar picture emerges from a study of the literature on such volcanoes as the Soufrière of St. Vincent, Merapi, and Lassen Peak, for the normal vulcanian explosion is a common feature of their overall activity. It is necessary to emphasize the intimate association between normal vulcanian and " Pelean " type activity because the importance of the normal vulcanian outburst in the total activity of an eruption producing laterally moving clouds is sometimes obscured by the attention given to nuées ardentes, which in their purest form have no vertical component.

Another feature which appears to be general among volcanoes of the Pelean type is that their activity is typically discontinuous. Some remain dormant for long periods. When a new cycle of activity begins the release of the stored energies is usually a series of discontinuous outbursts which may occur over many months, and even an individual paroxysm is characteristically a discontinuous process. Lacroix (1904, p. 164) observes of the paroxysmal explosions: " Elles étaient le résultat d'explosions repetées, produites, selon toute vraisemblance, au voisinage d'une ouverture de sortie *béante*. Chacune de ces explosions donnait ainsi naissance à une poussée de volutes, s'emboîtant dans celles de la poussée précédente et donnant comme resultante l'apparence d'une poussée continué ". He is referring to vertical projections. The grand paroxysms were apparently made up of a series of outbursts some of which distributed their ejecta laterally, and others vertically. Most of the laterally discharged nuées which Lacroix actually saw in the winter of 1902-3 were produced by a single abrupt discharge (1904, p. 200). There were exceptions: the nuée of 16th December 1902 was produced by a continuous series of outbursts lasting fifteen minutes, and on 24th February 1903 the explosive series which made up the lateral discharge lasted 22 minutes. Perret (1937, p. 89) in discussing the mechanism of the nuée formation observes: " Emission was not continuous; the material did not flow from the vent but the ejections followed one another at such brief intervals as to form an unbroken procession of nuées ardentes ".

The inherent discontinuity of the Pelean mode of emission and the " mixed " nature of the explosive outbursts is well illustrated by the phenomena of the Mt. Lamington eruption. Some of the outbursts were purely vulcanian; in others the power of projection had dropped to such a low level that the outbursts seemed no more than massive disgorgements of fragmental material. Between these extremes both types of projection were confusingly mixed in that some of their load was dropped about the crater, and at the same time a great ash column, rising many thousands of feet, was pushed above the volcano.

The Spear-head Projections.

Let us first examine a " microform " of the eruptive activity, the spear-head projection. It consisted of small jets of ash and gas which were projected to heights rarely exceeding 2,000 feet (see fig. 26). Essentially rhythmical, these projections would sometimes continue for hours at intervals varying from a minute to several minutes. They seem to have been produced by a limited vesiculation process which lagged in a more or less regular fashion behind the change in pressure conditions introduced by each successive release.

The phenomena were most prevalent during the early stages of the dome growth, when the floor of the crater was being lifted from the conduit and the carapace was presumably thin. The explosions persisted until quite a later stage in the development of the first dome, but their power waned appreciably towards the end. They appeared finally to degenerate into the pulses of activity which produced the small nuées and avalanches from the flanks of the dome.

Sometimes an explosion of this type would become overloaded with ejecta and the usual slender column would be replaced by a black expanding cone-shaped mass of ejecta which, on collapsing, formed an embryo nuée. An explosion of this type was photographed on 30th January 1951 (figs. 21 to 25). Figure 21 illustrates the usual type of rhythmical explosion as seen from the airstrip; figure 22 the cone-shaped projection; in figure 23 the collapsed material has formed a coherent flat-lying cloud moulded on the dipping surface of the crater floor into a wide V and flowing down the slopes towards the north; in figure 24 the embryo nuée reaches the northern edge of the uplifted crater floor and disperses through lack of material to give it further momentum; in figure 25, a few minutes later, the activity of the south-eastern vent on the left-hand side of the photograph is confined to vapour emission, and mild, predominantly gaseous, projections are proceeding from a vent at the base of the southern wall.

The vents which produced the spear-head projections were first located on the margins of the crater floor, chiefly on the southern sector of the crater. Later vents developed on the summit and flanks of the rising dome. Since, in the past, this aspect of this type of eruption has been largely a matter of conjecture, the location of vents is treated more fully later.

Shallow-pocket Explosions.

On several occasions the discrete explosive events of the spear-head type gave way to a mass effect. Successive explosions fountained rapidly and extensively from many parts of the crater floor and filled the crater bowl with a massive convoluted cloud of fragmental lava and gas. The cloud usually showed little tendency to rise. The heavy, yet buoyant, mass seemed to behave as a layered hydrostatic column raised in the bowl of the crater. The heavier fractions poured out through the low gaps in the crater wall; the lighter fractions poured over the crater rim.

The mass effect, the absence of a powerful vertical component, and the absence of distinctive seismic movement, together suggest that an eruption of this type derives all its material from a shallow source. A body of magma, located in the upper part of the conduit, is brewed until it attains a critical condition; whereupon, a massive vesiculation process lifts it bodily out of its pocket on to the crater floor and continued vesiculation supplies the gas to give it the curious buoyancy and hydrostatic properties which enable it to flow as a fragmental mass. Perret (1937, page 86) considered that

Owing to an oversight, Figs. 13-20 are numbered as Figs. 11-18.

GRAPHICAL SUMMARY OF THE EARLY EXPLOSIVE AND SEISMIC ACTIVITY MT LAMINGTON

JANUARY - MARCH 1951

Reference

- Normal explosive ejection of ash
- Steam explosion
- Continuous emission of ash
- Continuous emission of vapour
- Broken column indicates height of ash or gas. column is estimated rather than accurately measured.
- Nuée ardente, with or without explosive origin.
- Explosion with suspected nuée ardente during conditions of poor visibility.
- TO Variations in magnitude of explosion indicated by thickness of line.

BUREAU OF MINERAL RESOURCES GEOLOGY & GEOPHYSICS - MAR. 1956

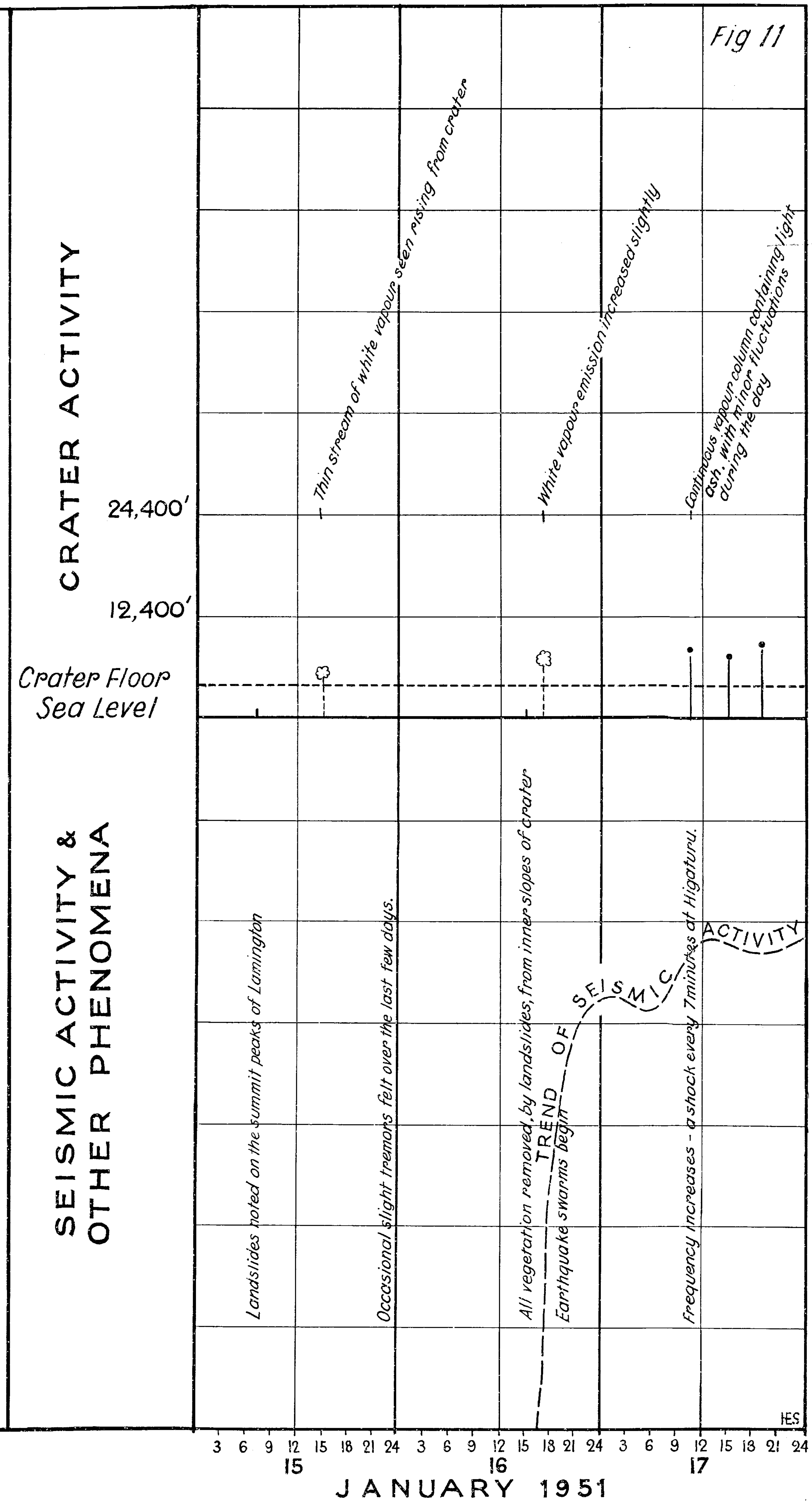
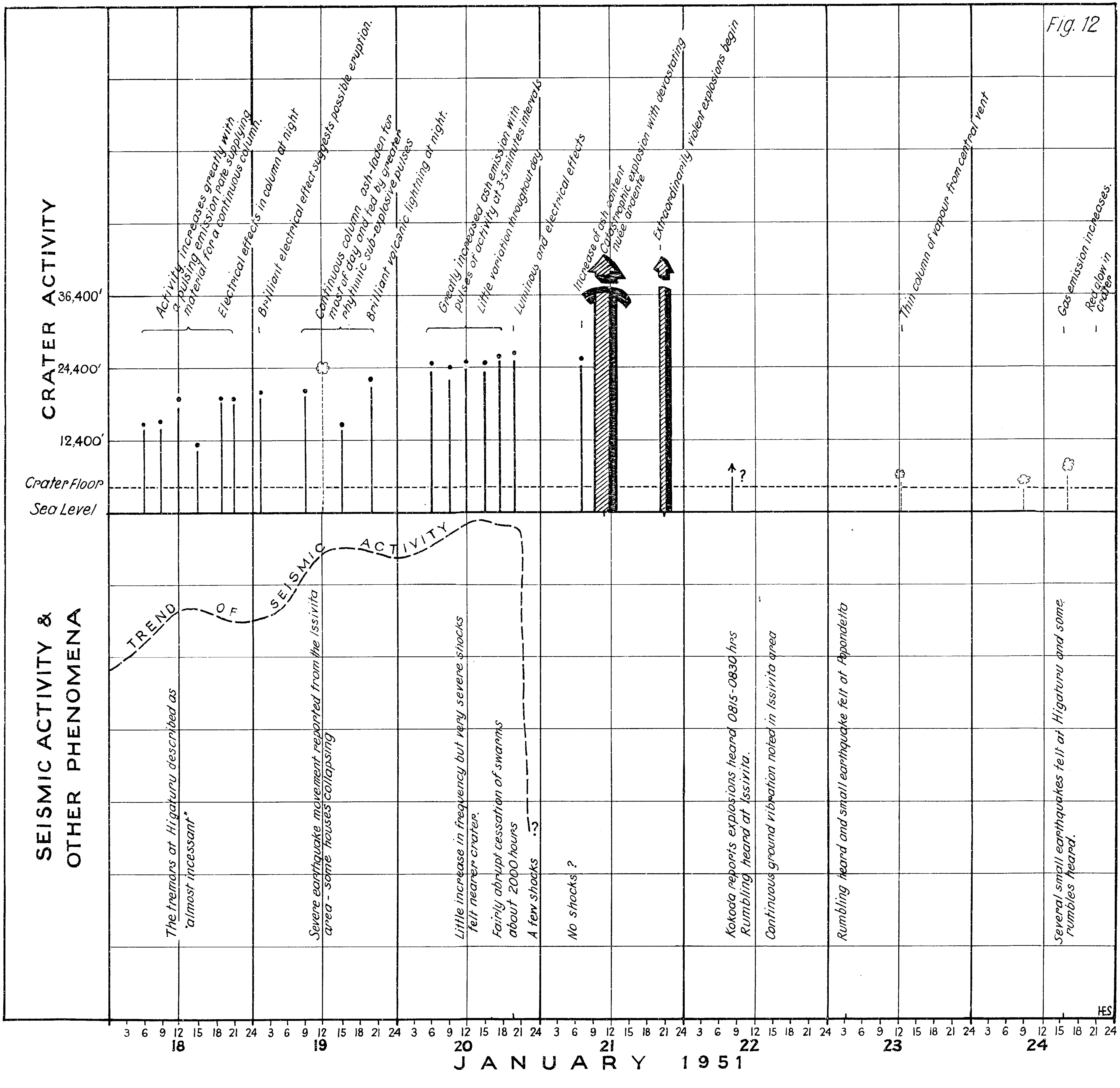


Fig. 12


CRATER ACTIVITY
36,400′
24,400′
12,400′
Crater Floor
Sea Level
Activity increases greatly with a pulsing emission rate supplying material for a continuous column.
Electrical effects in column at night
Brilliant electrical effect suggests possible eruption.
Continuous column ash-laden for most of day and fed by greater rhythmic sub-explosive pulses
Brilliant volcanic lightning at night.
Greatly increased ash emission with pulses of activity at 3-5 minutes intervals
Little variation throughout day
Luminous and electrical effects
Increase of ash content
Catastrophic explosion with devastating nuée ardente
Extraordinarily violent explosions begin
Thin column of vapour from central vent
Gas emission increases.
Red glow in crater
SEISMIC ACTIVITY & OTHER PHENOMENA
TREND OF SEISMIC ACTIVITY
The tremors at Higaturu described as "almost incessant"
Severe earthquake movement reported from the Issivita area - some houses collapsing
Little increase in frequency but very severe shocks felt nearer crater.
Fairly abrupt cessation of swarms about 2000 hours
A few shocks
No shocks ?
Kokoda reports explosions heard 0815-0830 hrs
Rumbling heard at Issivita.
Continuous ground vibration noted in Issivita area
Rumbling heard and small earthquake felt at Popondetta
Several small earthquakes felt at Higaturu and some rumbles heard.
HES
18
19
20
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23
24
JANUARY 1951

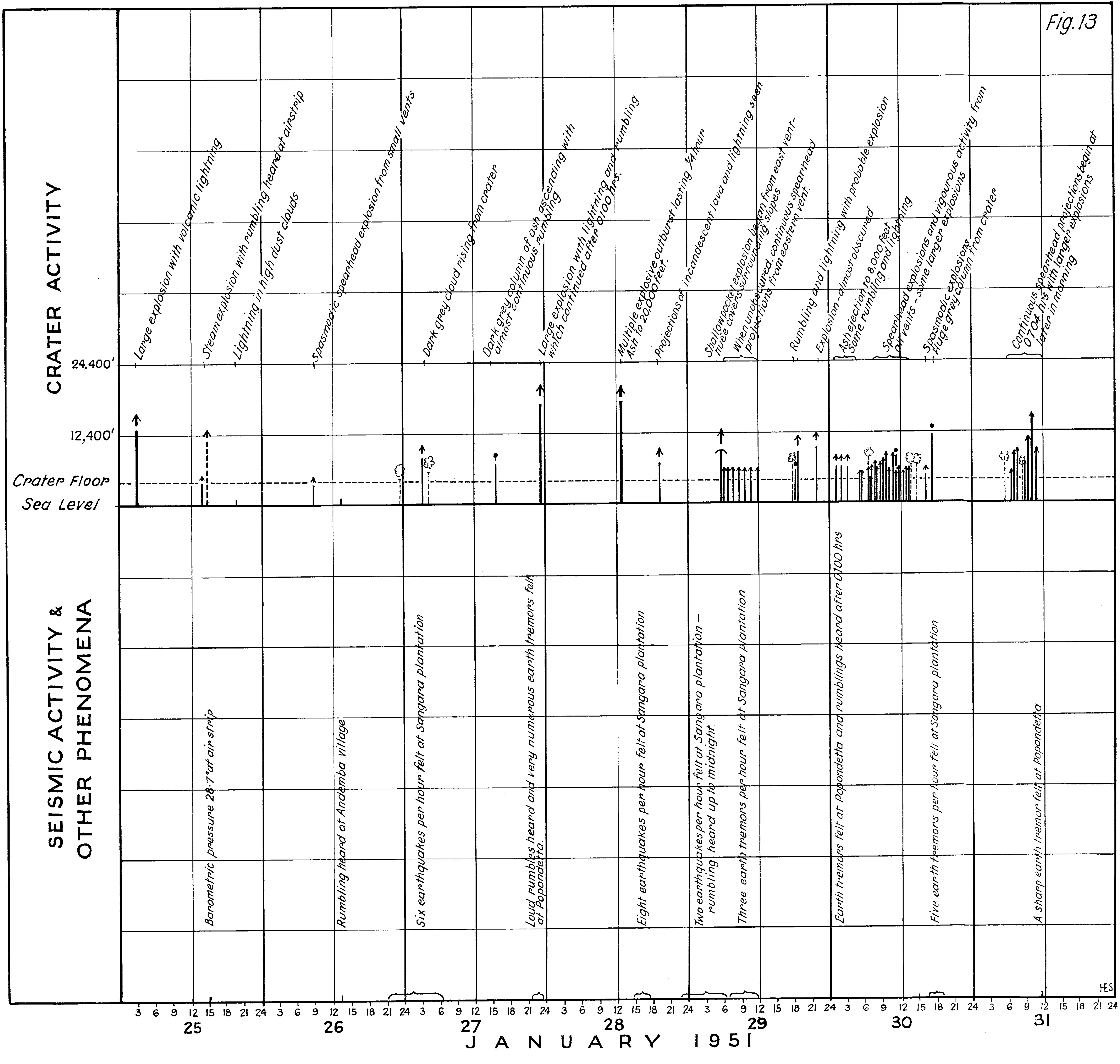


Fig. 13
CRATER ACTIVITY
24,400'
12,400'
Crater Floor
Sea Level
Large explosion with volcanic lightning
Steam explosion with rumbling heard at airstrip
Lightning in high dust clouds
Spasmodic spearhead explosion from small vents
Dark grey cloud rising from crater
Dark grey column of ash ascending with almost continuous rumbling
Large explosion with lightning and rumbling which continued after 0100 hrs.
Multiple explosive outburst lasting 1/4 hour Ash to 20,000 feet.
Projections of incandescent lava and lightning seen
Shallow pocket explosion began from east vent - nuée covers surrounding slopes
When unobscured, continuous spearhead projections from eastern vent.
Rumbling and lightning with probable explosion
Explosion - almost obscured
Ash ejection to 8,000 feet Some rumbling and lightning
Spearhead explosions and vigourous activity from all vents - some larger explosions
Spasmodic explosions Huge grey column from crater
Continuous spearhead projections begin at 0704 hrs with larger explosions later in morning
SEISMIC ACTIVITY & OTHER PHENOMENA
Barometric pressure 28.7" at air strip
Rumbling heard at Andemba village
Six earthquakes per hour felt at Sangara plantation
Loud rumbles heard and very numerous earth tremors felt at Popondetta.
Eight earthquakes per hour felt at Sangara plantation
Two earthquakes per hour felt at Sangara plantation - rumbling heard up to midnight.
Three earth tremors per hour felt at Sangara plantation
Earth tremors felt at Popondetta and rumblings heard after 0100 hrs
Five earth tremors per hour felt at Sangara plantation
A sharp earth tremor felt at Popondetta
FES
3 6 9 12 15 18 21 24
25 26 27 28 29 30 31
JANUARY 1951

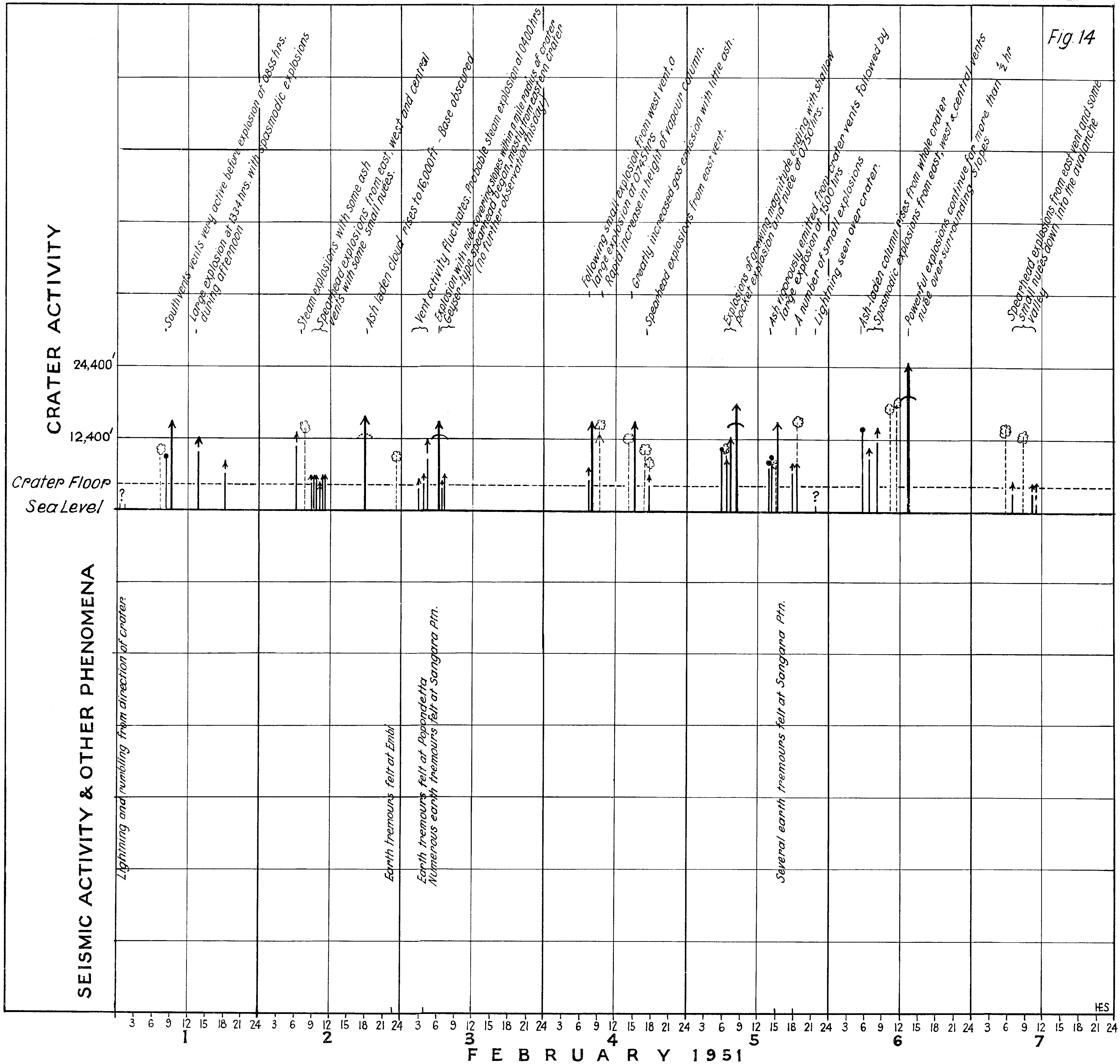

CRATER ACTIVITY
24,400'
12,400'
Crater Floor
Sea Level
- South vents very active before explosion at 0855 hrs.
- Large explosion at 1334 hrs. with spasmodic explosions during afternoon
- Steam explosions with some ash
Spearhead explosions from east, west and central vents with some small nuées.
- Ash laden cloud rises to 16,000 ft - Base obscured
Vent activity fluctuates: Probable steam explosion at 0400 hrs
Explosion with nuée covering slopes within a mile radius of crater
Geyser-type spearhead began, mostly from eastern crater (no further observation this day)
Following small explosion from west vent, a large explosion at 0745 hrs
Rapid increase in height of vapour column.
- Greatly increased gas emission with little ash.
- Spearhead explosions from east vent.
Explosions of growing magnitude ending with shallow pocket explosion and nuée at 0750 hrs.
- Ash vigorously emitted from crater vents followed by large explosion at 1500 hrs
- A number of small explosions
- Lightning seen over crater.
- Ash-laden column rises from whole crater
Spasmodic explosions from east, west & central vents
- Powerful explosions continue for more than ½ hr nuée over surrounding slopes
Spearhead explosions from east vent and some small nuées down into the avalanche valley
SEISMIC ACTIVITY & OTHER PHENOMENA
Lightning and rumbling from direction of crater
Earth tremours felt at Embi
Earth tremours felt at Popondetta
Numerous earth tremours felt at Sangara Ptn.
Several earth tremours felt at Sangara Ptn.
3 6 9 12 15 18 21 24
1 2 3 4 5 6 7
FEBRUARY 1951
HES

Fig. 14

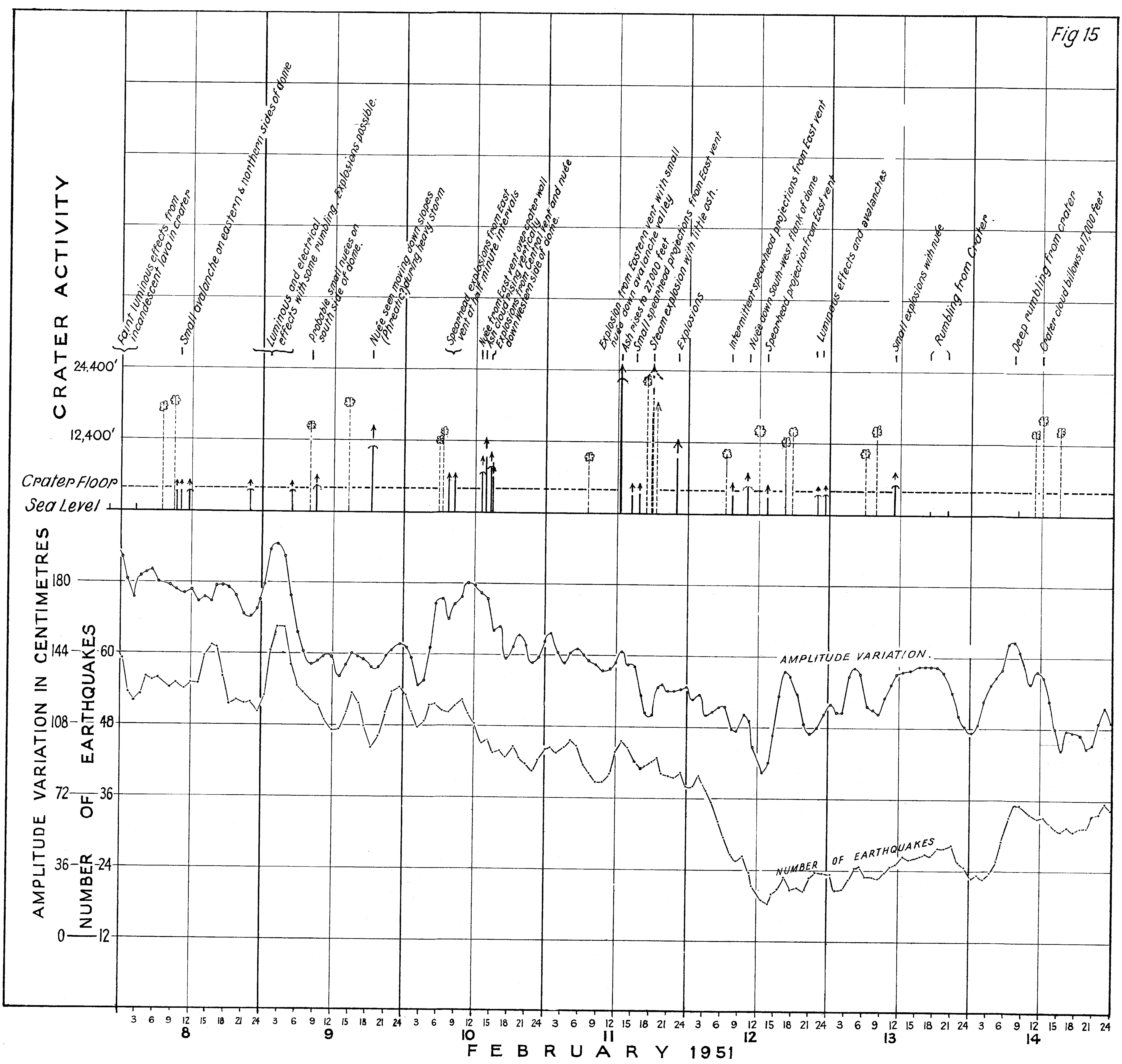
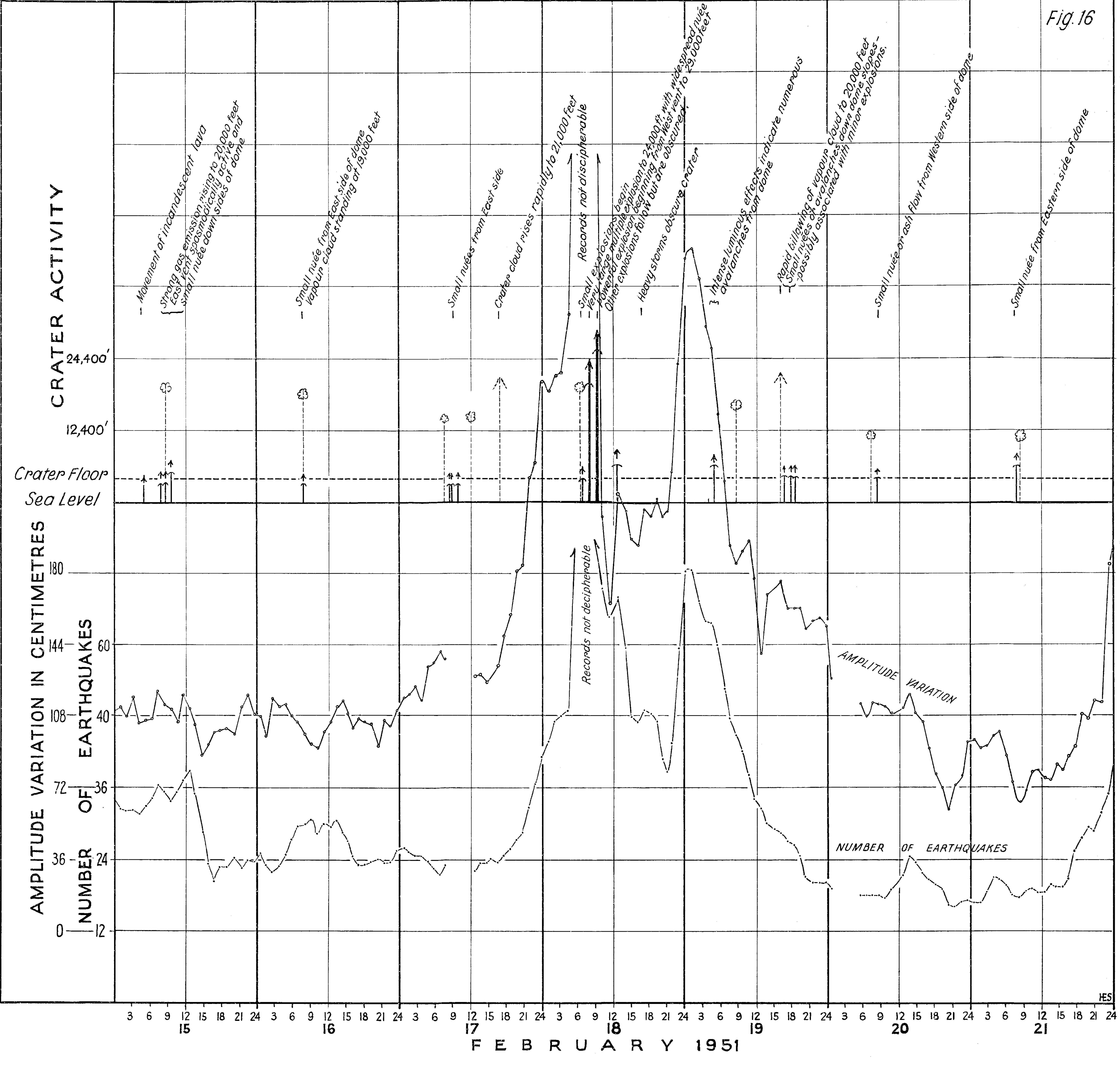


Fig 15
CRATER ACTIVITY
Faint luminous effects from incandescent lava in crater
Small avalanche on eastern & northern sides of dome
Luminous and electrical effects with some rumbling
Probable small nuees on south side of dome. Explosions possible.
Nuée seen moving down slopes (Phreatic) during heavy storm
Spearhead explosions from East vent at half minute intervals
Nuée from East vent over crater wall
Ash cloud rising vertically
Explosions from Central vent and nuée down western side of dome.
Explosion from Eastern vent with small nuée down avalanche valley
Ash rises to 27,000 feet
Small spearhead projections from East vent
Steam explosion with little ash.
Explosions
Intermittent spearhead projections from East vent
Nuée down South-west flank of dome
Spearhead projection from East vent
Luminous effects and avalanches
Small explosions with nuée
Rumbling from Crater.
Deep rumbling from crater
Crater cloud billows to 17,000 feet
24,400'
12,400'
Crater Floor
Sea Level
AMPLITUDE VARIATION IN CENTIMETRES
NUMBER OF EARTHQUAKES
180
144
108
72
36
0
60
48
36
24
12
AMPLITUDE VARIATION.
NUMBER OF EARTHQUAKES
8
9
10
11
12
13
14
FEBRUARY 1951

Fig. 16



CRATER ACTIVITY
Movement of incandescent lava
Strong gas emission rising to 20,000 feet
East vent spasmodically active and
Small nuée down sides of dome
Small nuée from East side of dome
Vapour cloud standing at 19,000 feet
Small nuées from East side
Crater cloud rises rapidly to 21,000 feet
Records not decipherable
Small explosions begin
Very large multiple explosion to 24,000 ft. with widespread nuée
Powerful explosion beginning from West vent to 29,000 feet
Other explosions follow but are obscured.
Heavy storms obscure crater
Intense luminous effects indicate numerous
avalanches from dome
Rapid billowing of vapour cloud to 20,000 feet
Small nuées or avalanches down dome slopes -
possibly associated with minor explosions.
Small nuée or ash flow from Western side of dome
Small nuée from Eastern side of dome
24,400′
12,400′
Crater Floor
Sea Level
AMPLITUDE VARIATION IN CENTIMETRES
NUMBER OF EARTHQUAKES
180
144
108
72
36
0
60
40
36
24
12
Records not decipherable
AMPLITUDE VARIATION
NUMBER OF EARTHQUAKES
3 6 9 12 15 18 21 24
15
16
17
18
19
20
21
FEBRUARY 1951
HES

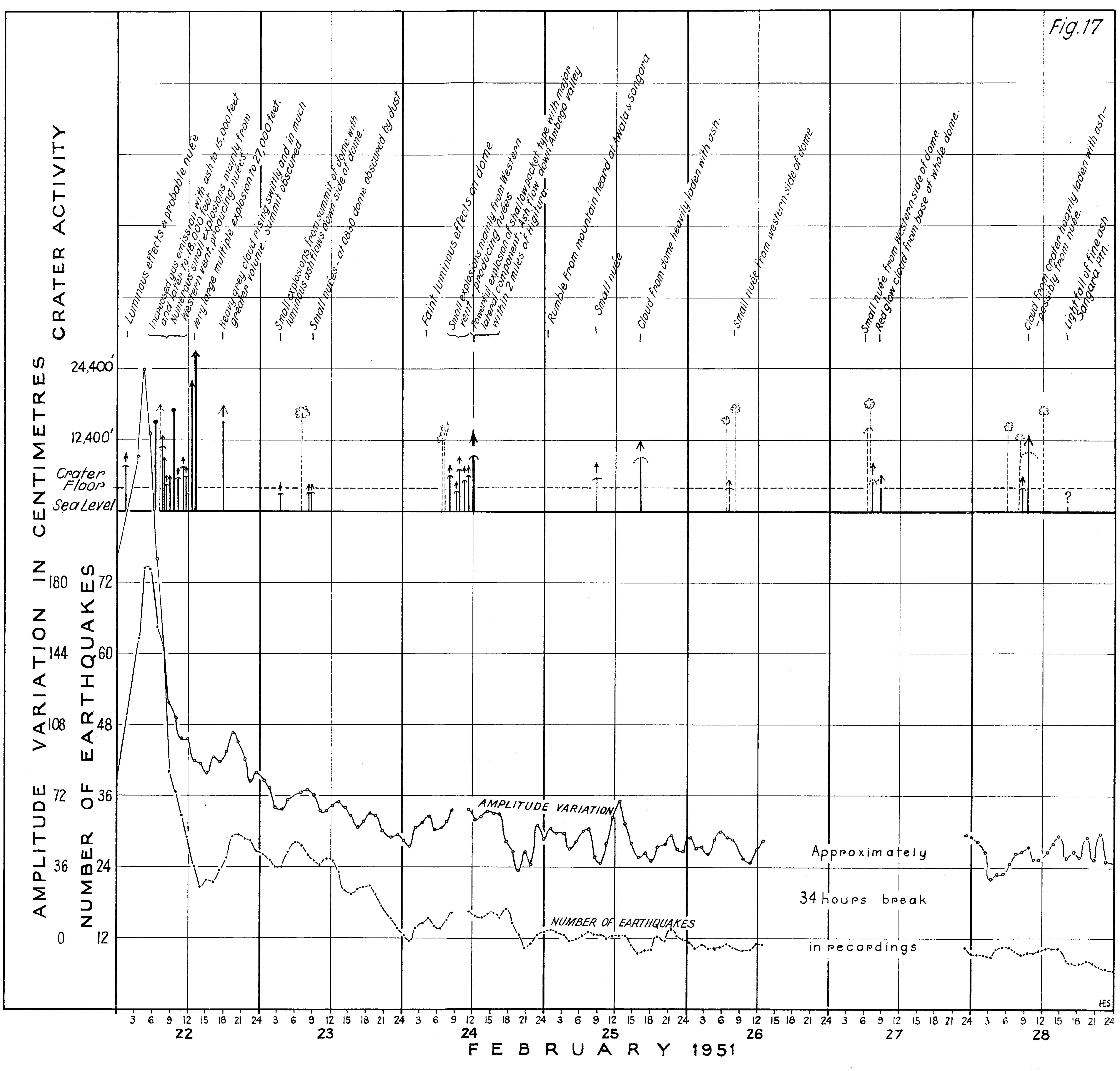


Fig.17
CRATER ACTIVITY
AMPLITUDE VARIATION IN CENTIMETRES
NUMBER OF EARTHQUAKES
Luminous effects & probable nuée
Increased gas emission with ash to 15,000 feet and later to 18,000 feet.
Numerous small explosions mainly from western vent, producing nuées.
Very large multiple explosion to 27,000 feet.
Heavy grey cloud rising swiftly and in much greater volume. Summit obscured
Small explosions from summit of dome with luminous ash flows down side of dome.
Small nuées - at 0830 dome obscured by dust
Faint luminous effects on dome
Small explosions mainly from Western vent producing nuées
Powerful explosion of shallow pocket type with major lateral component. Ash flow down Ambogo valley within 2 miles of Higitura.
Rumble from mountain heard at Awala & Sangara
Small nuée
Cloud from dome heavily laden with ash.
Small nuée from western side of dome
Small nuée from western side of dome
Red glow cloud from base of whole dome.
Cloud from crater heavily laden with ash - possibly from nuée.
Light fall of fine ash Sangara Ptn.
24,400'
12,400'
Crater Floor
Sea Level
AMPLITUDE VARIATION
NUMBER OF EARTHQUAKES
Approximately 34 hours break in recordings
FEBRUARY 1951
22
23
24
25
26
27
28

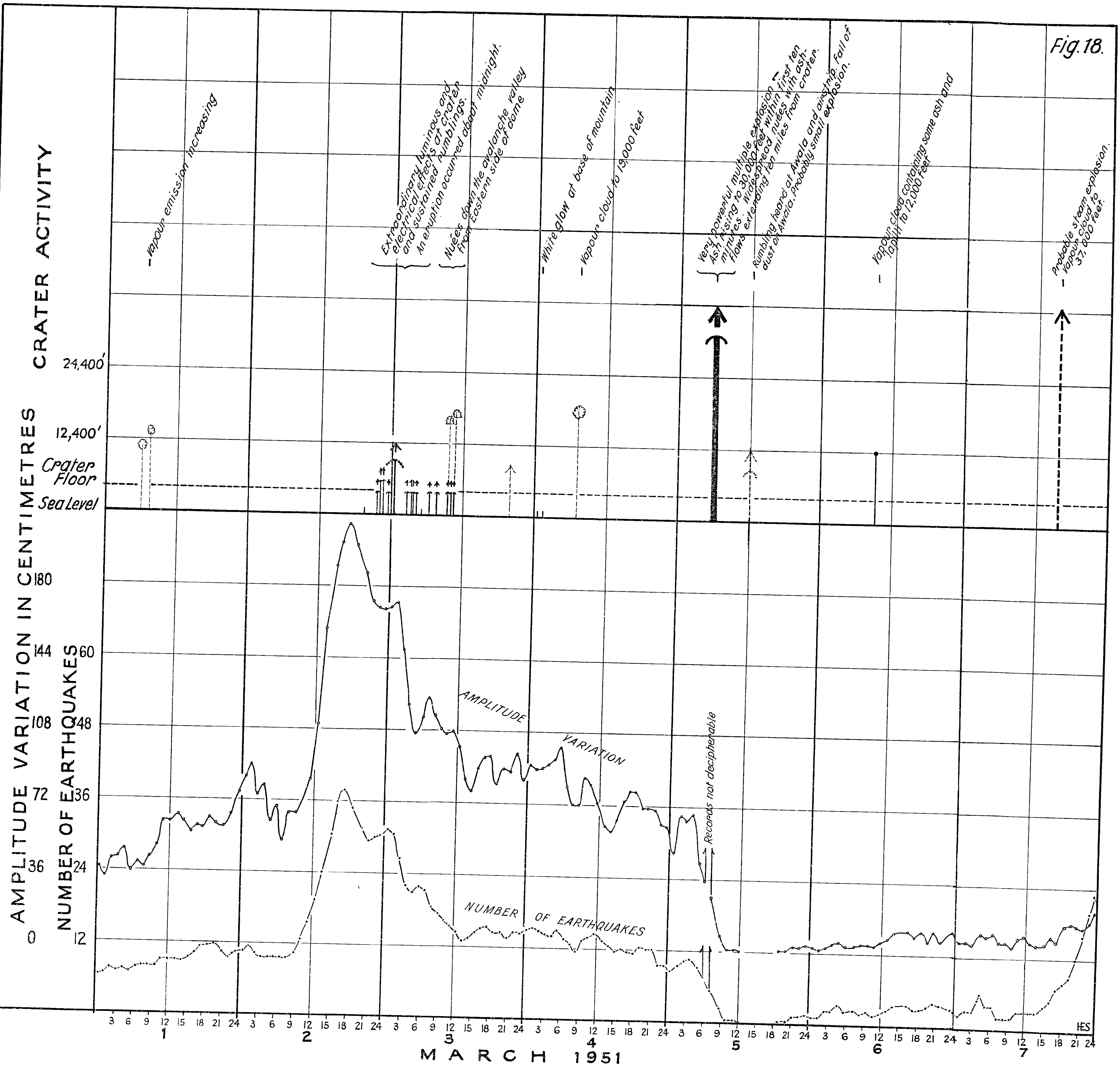


Fig. 18.
CRATER ACTIVITY
- Vapour emission increasing
Extraordinary luminous and electrical effects at crater and sustained rumblings.
An eruption occurred about midnight.
Nuées down the avalanche valley from Eastern side of dome
- White glow at base of mountain
- Vapour cloud to 19,000 feet
Very powerful multiple explosion. Ash rising to 30,000 feet within first ten minutes. Widespread nuées with ash-flows extending ten miles from crater.
Rumbling heard at Awala and airstrip. Fall of dust on Awala. Probably small explosion.
Vapour cloud containing some ash and lapilli to 12,000 feet
Probable steam explosion. Vapour cloud to 37,000 feet.
24,400′
12,400′
Crater Floor
Sea Level
AMPLITUDE VARIATION IN CENTIMETRES
NUMBER OF EARTHQUAKES
180
144
108
72
36
0
60
48
36
24
12
AMPLITUDE VARIATION
NUMBER OF EARTHQUAKES
Records not decipherable
3 6 9 12 15 18 21 24
1
2
3
4
5
6
7
MARCH 1951
HES

Fig. 21. 30.1.51. A small spearhead explosion, seen from Popondetta airstrip, 11½ miles away.

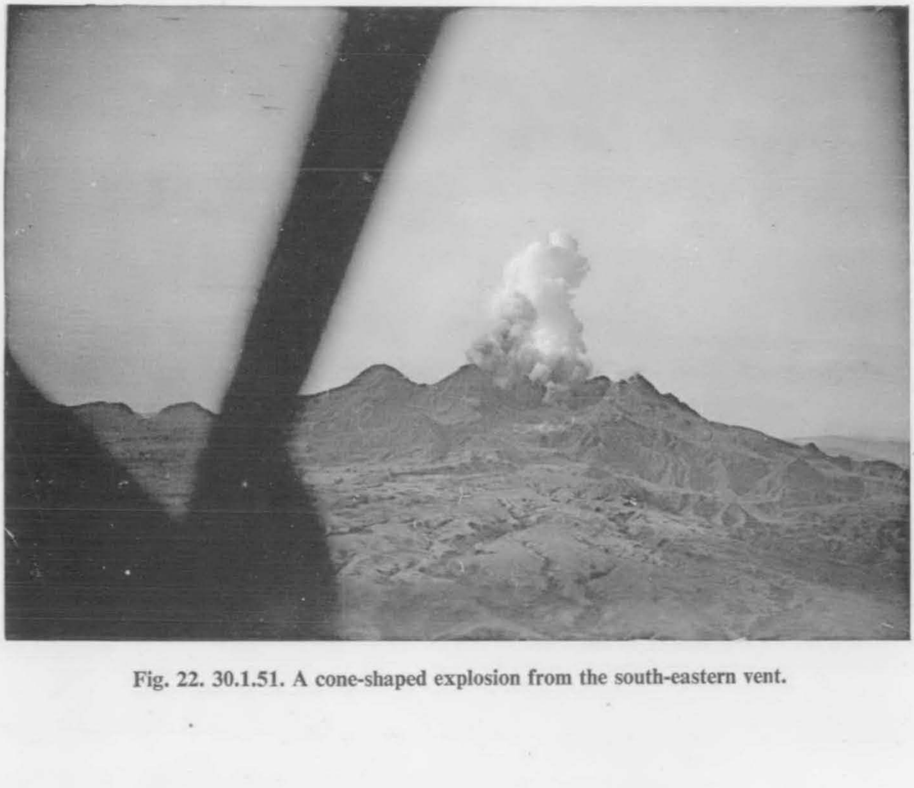


Fig. 22. 30.1.51. A cone-shaped explosion from the south-eastern vent.

Fig. 23. 30.1.51. A flat basal cloud of fragmental lava has now formed.

Fig. 24. 30.1.51. The basal cloud expands and disperses before it can descend into the avalanche valley.

Fig. 25. 30.1.51. Crater activity a few minutes after the explosion.

Fig. 26. 31.1.51. Explosion of spear-head projection type rising from vent on S.W. side of crater. Column about 1,500 feet high.

[*To face page* 32.]

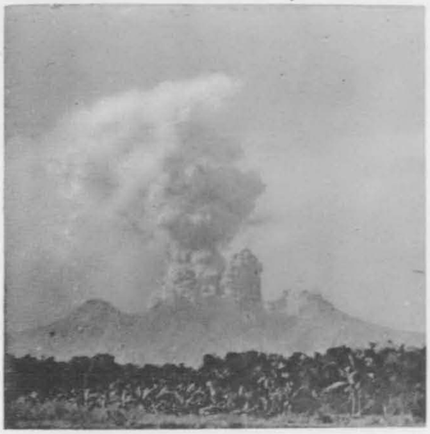


Fig. 27.

Fig. 28.

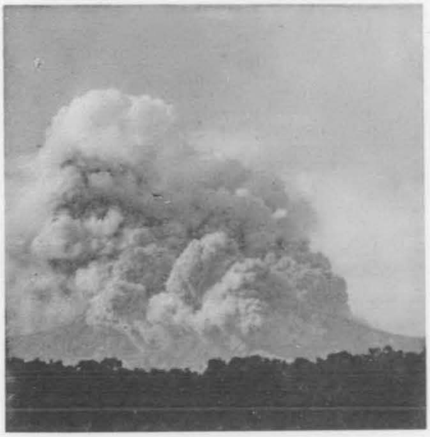


Fig. 29.

Fig. 30.

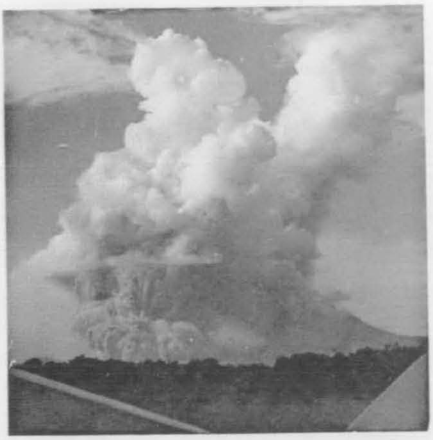


Fig. 31.

Fig. 32.

Figs. 27-32. 5.2.51. A shallow-pocket eruption.

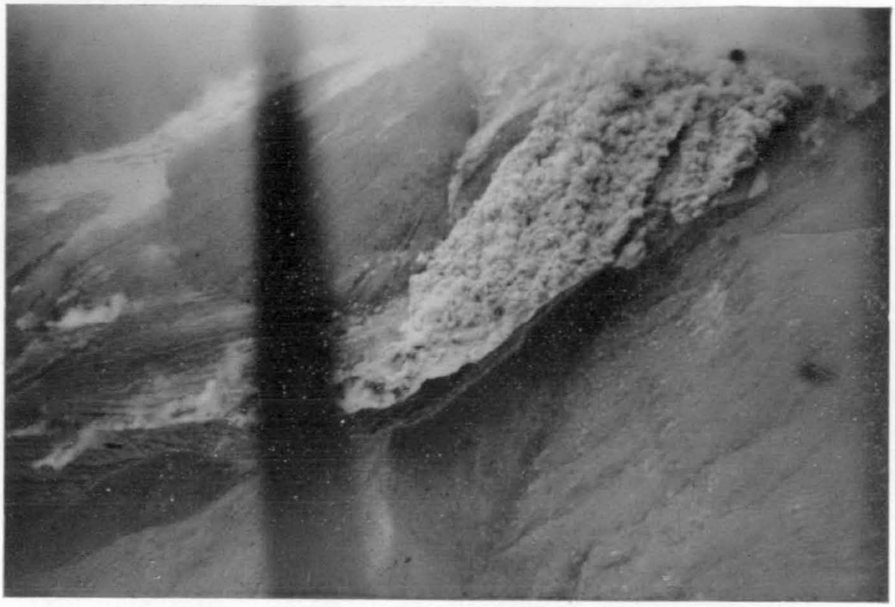


Fig. 33. 24.2.51. Sheet-flow avalanches descending the N.W. flank of the dome.

Fig. 34. A quick diffusion of the cauliflower convolutions indicates a low gas content.

Fig. 35. 22.2.51. The development of a small nuée ardente: (1) the nuée moves as a flat compact mass.

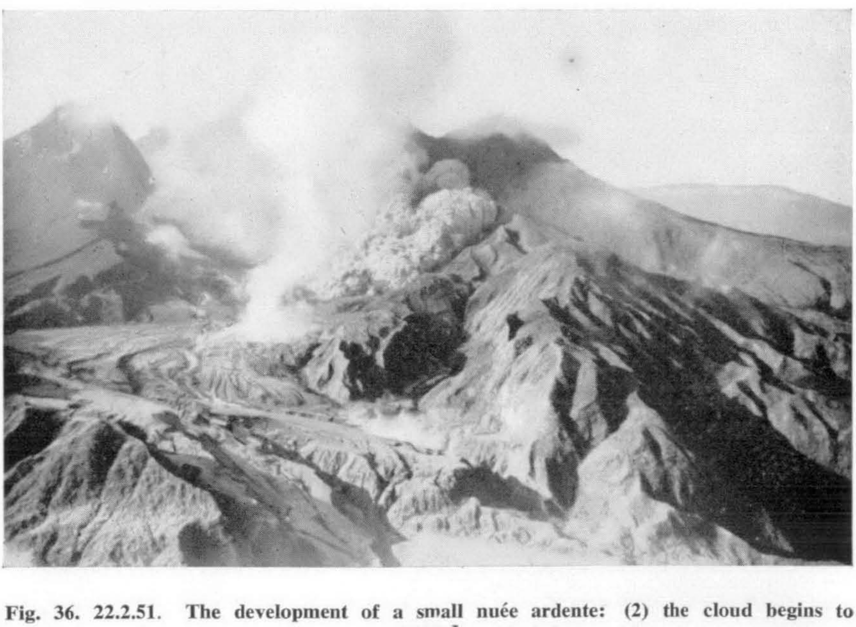


Fig. 36. 22.2.51. The development of a small nuée ardente: (2) the cloud begins to expand.

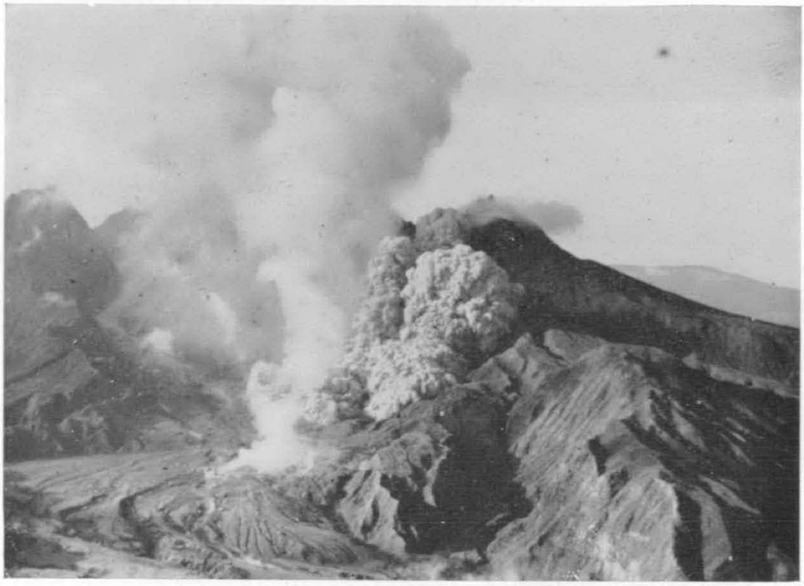


Fig. 37. 22.2.51. The development of a small nuée ardente: (3) forward movement slows and upward expansion increases.

Fig. 38. 22.2.51. The development of a small nuée ardente: (4) voluminous clouds rise from the slow-moving nuée.

Fig. 39. 5.3.51. Development of a nuée ardente: (1) clouds rise from the approaching nuée.

Fig. 40. 5.3.51. Development of a nuée ardente: (2) two streams advance down river valleys.

Fig. 41. 5.3.51. Development of a nuée ardente: (3) the advance marks the course of the Ambogo Valley.

Fig. 42. 5.3.51. Development of a nuée ardente: (4) the nuée swings to the left of the picture, following a change in direction of the valley.

Fig. 43. 5.3.51. Development of a nuée ardente: (5) the nuée passes the Observation Post.

Fig. 44. 5.3.51. Development of a nuée ardente: (6) the diffused upper layers of the cloud begin to fall.

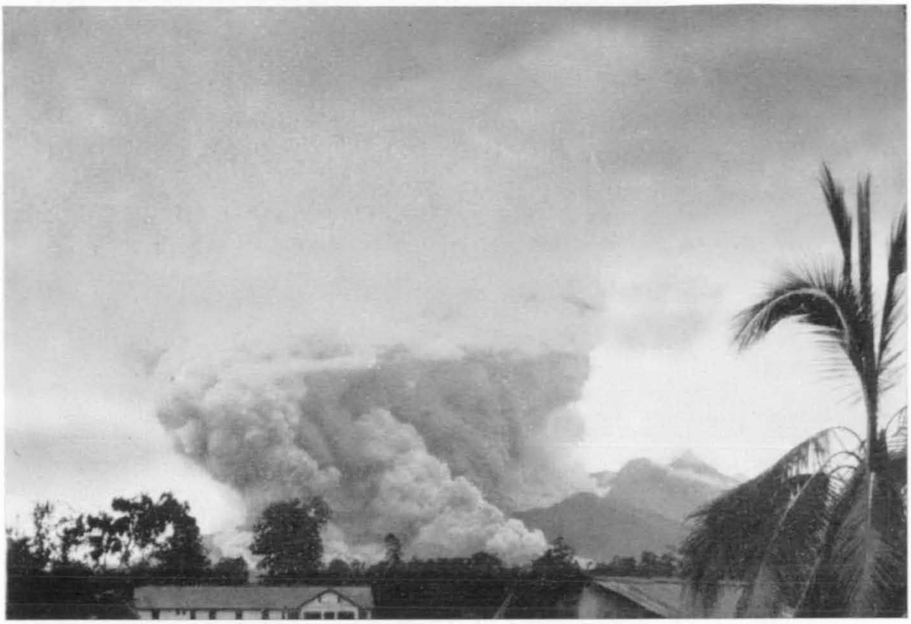


Fig. 45. 18.2.51. A component of the 0822 hrs. nuée moves down the upper Ambogo valley.

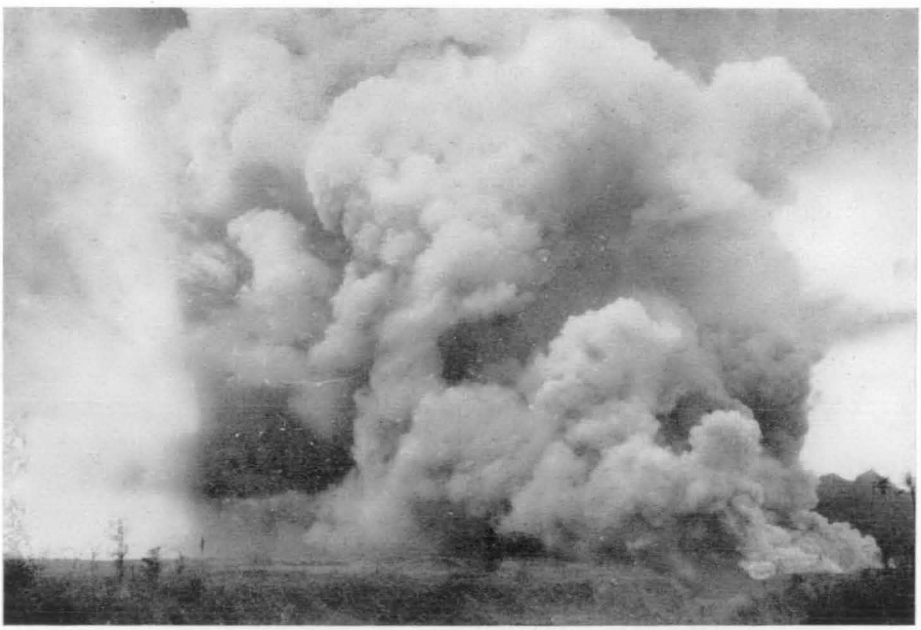


Fig. 46. 18.2.51. The nuée in the Ambogo valley stops about 2 miles from Higaturu.

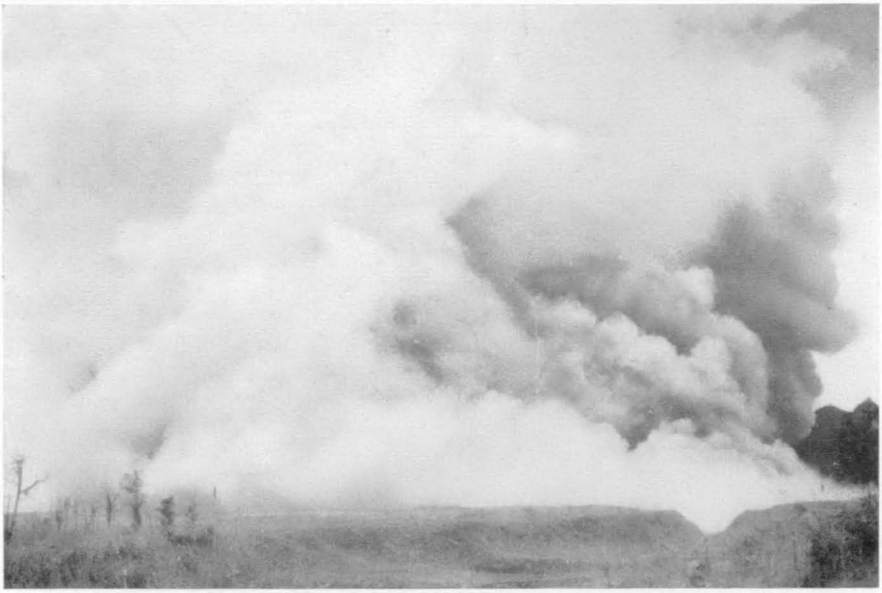


Fig. 47. 18.2.51. The slopes are enveloped by clouds expanding from the nuée deposit.

Fig. 48. 18.2.51. 0933 hrs. Ash column rising about 6 miles above crater. Viewed from Popondetta airstrip.

Fig. 49. 11.2.51. Approaching crater through avalanche valley. The vent on the left of the dome is showing destructive activity.

Fig. 50.

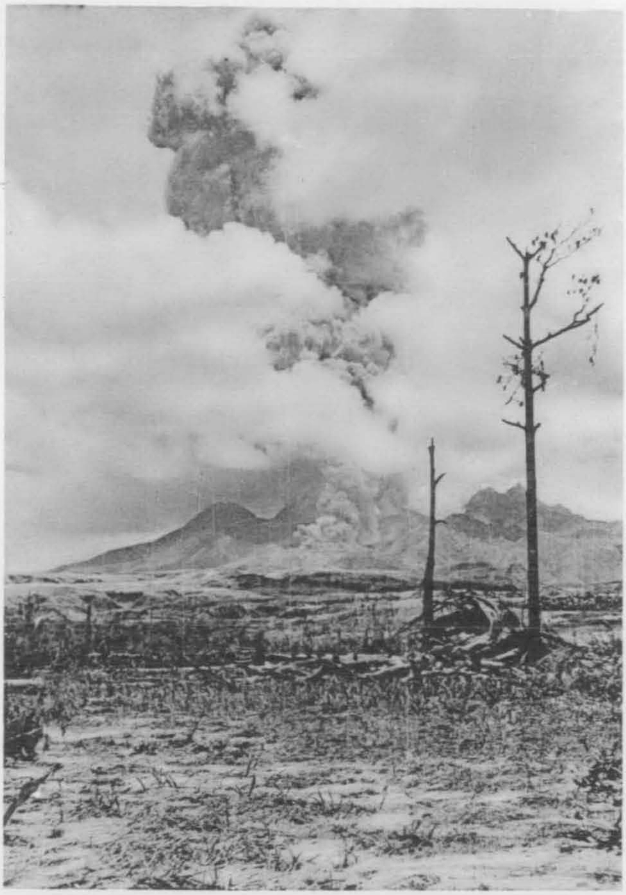


Fig. 51.

Figs. 50-51. 11.2.51. A shallow-pocket eruption.

this auto-explosive and self-projecting property of a shallow magma pocket constituted the essential difference between an explosion that produced a nuée ardente and one that produced a normal vertical projection.

With a normal outburst, the explosion came from an extraneous source and the shallow magma was inert. It is apparent that, in some eruptions, both these processes operate either concurrently or in succession; but first let us examine examples of the shallow-pocket manifestations.

On 5th February 1951, the development of an eruption of this type was photographed from the Popondetta airstrip. The eruption began with a series of small explosions in the southern sector and over the full width of the crater floor (fig. 27). Some material could be seen moving through the low south-eastern gap. With further explosions (fig. 28) the whole bowl of the crater filled with a huge seething cloud of ash, and a nuée moved down the avalanche valley towards the camera (fig. 29). At the same time, part of the cloud spilled over the western rim of the crater and began to descend. Gradually the cloud lost its appearance of close-knit compactness and became diffuse (fig. 30). The small cloud on the western slope expired for want of gas-producing fragmental fuel and a few minutes later it had disappeared (fig. 31). The main cloud, however, which descended over the north-eastern slopes, was rejuvenated, for a short time, by the arrival of a later nuée. Not long afterwards the diffused remnants of the nuée ardente drifted to the east and revealed vigorous vapour emission from the crater and a light-coloured deposit of new ash on the floor of the avalanche valley (fig. 32). Twenty-two minutes had elapsed between the initial explosion and the return of clear visibility.

Because the rapidity of movement, from the crater environs, of the gas-emitting nuée ardente is essentially controlled by gravity, the form, size and duration of the crater cloud in an eruption of this type may be governed to a large extent by the topography both of the crater and of the immediate slopes. On 5th February, the symmetrical crater ring, between the centrally placed dome and the walls, was practically flat, and below it the avalanche valley sloped away at no more than 5°. The cloud tended to dwell in, and fill, the crater bowl since neither the internal nor external slopes favoured the rapid exit of the disgorged lava mass. In contrast, Pelée at an early stage of the activity of 1902 had a sloping crater ring which was due, in part, to the welding to the north-western wall of the asymmetrically placed dome. In effect, it was a spiral descending into the head of the avalanche valley, which had an initial slope of the order of 30° (Hovey, 1902, page 341). It would be difficult to conceive of conditions more ideally suited to the rapid removal from a crater of a nuée discharged into such a crater ring. Such a structure would swiftly concentrate the scattered elements of nuée explosions into a single stream which would pour through the breach into the steep River Blanche valley and move rapidly through the valley to the sea. Perhaps this was the explanation of the abrupt appearance and descent of some of the nuées from Pelée and also the rapid clearing of the crater which followed. The comparative sluggishness of similar events at Lamington seems largely a matter of less sympathetic structure and terrain.

The largest observed shallow-pocket eruption occurred on 24th February. The main body of its nuée proceeded down the avalanche valley, but some of it spilled over the high crater walls on to the surrounding slopes. The distribution of this nuée may have been governed by factors similar to those that controlled the nuée which overwhelmed the Morne Rouge on 30th August 1902. At this time additional victims were claimed from an area which, because it had been shielded by high crater walls, had been untouched by the earlier paroxysms of Pelée.

The prelude to the eruption resembled the phenomena which preceded some of the eruptions of Pelée. It was confined to rumbling and to preliminary nuées and was without specific seismic movement; the seismic records revealed no distinctive features immediately preceding or during the outburst (fig. 19). During the previous 24 hours the western side of the dome had been markedly uplifted and its summit thickened. Continued movement was suggested by avalanches from the western flanks during the morning. The crater was examined at 0730 hours, when curious sheet-flow avalanches were descending an extensive section of the north-western dome flank (fig. 33). These avalanches resembled nuées in that they consisted of boiling clouds of dust which rose up and concealed their moving bases. A limited mobility and a quick diffusion (fig. 34) of the convoluted clouds, however, placed them in the category of an avalanche rather than in that of a nuée. Spasms of sustained rumbling began at 0740 hours and occurred throughout the morning. Less than half an hour after the rumbling began, a small nuée descended into the avalanche valley, followed by larger nuées, all originating from the western side of the crater. At 0930 hours a series of explosions repeated developments which accompanied the eruption of 5th February. The main nuée descended as usual from the western sector of the crater ring into the avalanche valley, and on this occasion the upper part of the cloud spilled over the western rim more voluminously than it had done previously. Within twenty minutes the crater had returned to normal. Activity was soon resumed, and large dark grey clouds of ash rose spasmodically from the western side of the crater and from adjacent sections of the avalanche valley until the culminating outburst.

This occurred at 1153 hours. The volcano was partially concealed at this time by broken cumulus cloud and the eruption was not seen clearly from the Sangara observation post until it was well developed. A huge cloud had ascended from the crater and was " mushrooming " at a low elevation above it. A nuée ardente had swept down the slopes of the volcano and the whole summit area appeared to be covered by laterally moving clouds of ash. The northern and western slopes only were ascertained to be covered by this nuée because the voluminous grey clouds ascending from the nuées on these slopes concealed from view other parts of the mountain.

The distribution of the nuée ardente was only confirmed by the relative intensity of the phenomena on the western and northern flanks. An examination of the deposits on the western slopes revealed that the nuée had left a fine-grained deposit of negligible thickness; the Ambogo valley contained a massive deposit of high-temperature ash which extended to a point 4 miles from the crater. The flows of mobile ash probably extended much farther on the less obstructed north-eastern slopes below the avalanche valley, but rain and another eruption prevented a more precise determination of the extent of the nuée. General impressions suggest that a buoyant, lightly laden fraction of the nuée swept over all sectors of the northern and western slopes to distances of 2 to 3 miles; the ponderous lower fraction, severely controlled by topography, extended at least twice as far in the valleys of the northern slopes.

The shallow pocket eruption, then, appears to be made up of a continuous series of small outbursts which produce the total effect produced above. An examination of a single component will perhaps make clearer the form and mechanism of the multiple event. A perfect example of such a component is provided by a small nuée ardente which was observed on the morning of 22nd February. Without violent initiation it descended from the western flank of the dome into the crater ring and down on to the floor of the avalanche valley. In the beginning it showed little tendency to expand, but moved down the valley floor as a flat-lying mass (fig. 35), with an appearance of remarkable compactness and vitality. In contrast to the sheet-flow avalanches (fig. 34), there was no appearance of diffusion; bulging nodular convolutions formed the turbulent surface of this flowing lava mass. As its forward momentum decreased the cloud expanded voluminously and rose at the rate of 2,400 feet per minute (figs. 36 to 38). The magnitude of the cloud derived from this very small nuée indicated the high gas content of the fragmental lava; it also indicated a high state of gas tension for the conduit lava generally, because a few hours later, at 1200 hours, a paroxysmal outburst occurred.

Vulcanian Explosions and Associated Nuées Ardentes.

In some respects the Peléan type volcano resembles a normal explosive volcano that has degenerated into a low-pressure activity while still retaining the power of voluminous discharge. The magma may be in such a physical condition that most of the outbursts are massive disgorgements of fragmental lava. In the course of an eruptive cycle, however, the volcano occasionally "reverts to type", producing normal vertical explosions, included among which may be vulcanian outbursts of great violence.

The largest purely vulcanian outburst from Lamington occurred at 2045 hours on 21st January 1951, ten hours after the catastrophic eruption. It was probably the most violent outburst of the whole eruptive cycle. According to people in the neighbourhood, it was a more noisy event than the morning eruption, and the explosions were heard as far afield as Finschhafen and Samarai. At the government station at Finschhafen, 175 miles north-west of Lamington, it was thought that a naval battle was in progress nearby, and the guard was called out. The eruption had an extremely powerful vertical trajectory: falls of ash heavier than the morning deposits were reported from Kokoda and other places west of the volcano. At Port Moresby, on the following morning, ash was still falling heavily enough to warrant the closing of the aerodrome because visibility was so limited. The only deposition near the crater was of scattered bombs, blocks, and a comparatively thin layer of ash. The outburst was evidently due to an enormous gas release which violently projected fine ash to great heights. It probably had affinities with Perret's "intermediate gas phase". Later vulcanian explosions followed this eruption, but none approached it in magnitude or violence.

The catastrophic paroxysm on the morning of 21st January, at 1040 hours, evidently combined in such close succession both high and low pressure ejection that the formation of the basal nuée ardente seemed to be the unfolding of a single enormous vertical explosion (fig. 10 to 12). The pressure presumably declined quickly after the first violent projection and great expanding masses of gas-charged ejecta were then poured onto the surrounding slopes. How long each successive phase lasted is a matter of conjecture; the duration of the vertical projection probably coincided with that of the continuous roar, which was estimated roughly as three or four minutes. The main nuée possibly lasted from five to ten minutes, and it is certain that smaller ones followed. An observer on the windward side noted that "the visibility had improved to four or five miles about half an hour after the eruption began"; another nuée was then seen descending the north-eastern slopes. This may have been one of the ash flows that left deposits in the valleys in this sector of the slopes (fig. 83).

The eruption of 5th March was the largest of the post-climax outbursts and produced a very large vulcanian cloud. The explosion was more notable, however, for a prolonged succession of ponderous nuées which passed beyond the limits of the original zone of devastation.

About half an hour before this explosion the column of vapour ascending from the crater was observed to be unusually thin. Gas emission was much less than on the previous day.* At 0558 hours a small earthquake was felt at the Sangara Observation Post and a moment later a brilliant display of stellar and chain lightning drew attention to the fact that an eruption had begun. A nuée covered all the upper slopes and a vertical column of ash ascended, to expand prodigiously above the volcano. A few minutes later the column was short and thick with massive lateral extensions at its base and summit. The whole column appeared to thicken as the gas clouds billowed up from the laterally moving material (fig. 39), and it soon became evident that the main nuée was flowing down the avalanche valley on to the north-eastern slopes, from more and more of which billowing ash clouds were rising. The western slopes were only part covered. Two streams then broke away from the main nuée and began flowing north in the direction of the Observation Post (fig. 40); the smaller one, on the left, followed the valley of the river which flows immediately east of Higaturu, and the larger one, in the centre of the photograph, followed the valley of the Ambogo River. The realization that the main body of the nuée ardente was being strictly controlled by topography was the only reassuring point in an alarming situation. The main north-easterly body of the nuée appeared to have already exceeded the limits of earlier devastation and the eruption showed still no sign of abating. The northerly component, in the Ambogo valley, appeared to be advancing at the rate of 30 miles per hour (fig. 41) and the lubricant gases from this river of fragmental lava boiled up in turbulent convolutions to form a great wall which marked the course of the river valley. Occasionally the advance clouds of the nuée would tend to become diffuse as if the gas supply were waning; then, a few minutes later, new bursts of energy revitalized the ash cloud with tightly woven convolutions (fig. 42). The nuée was evidently a multiple event consisting of a series of successive over-riding components.

Until the nuée approached the Observation Post the only sounds produced by the eruption had been an occasional rumble, as of thunder, and the distant crackling of stellar lightning when the first cloud rose above the volcano. As the nuée moved closer, however, a curious "rustling" noise was heard. The quality of this sound is perhaps best described as midway between a "swishing" and a "dry rustling". The sound was not notable for its loudness, but as the nuée passed east of the Observation Post, and about 700 yards from it (fig. 43) this gigantic "rustling" was not unlike a muted roar. It was quite loud enough to be heard by Mr. Harbeck above the noise of his unmuffled jeep, which was approaching the Observation Post along the northern road and moving almost parallel with, but in the direction opposite to, the nuée.

At 0620 hours the great turbulent wall of rising vapour and ash stood thousands of feet above its source. Gradually, as the summit spread overhead, the diffused yellowish grey upper layers folded over and began to descend slowly in curtain-like drapes (fig. 44). At this point it was surprising to see white flakes fluttering down from the dark folds of the cloud. These flakes proved to be leaves torn from the

* Perret attributed similar developments at Pelée to fluxing of the lava and to the temporary stoppage of the numerous small vents in the upper part of the conduit.

trees bordering the Ambogo valley and borne aloft by the rising ash clouds. Although still warm when they reached the ground they were quite uncharred; the white colour was derived from a coating of very fine ash. At 0628 a fine-grained pisolitic ash began to fall, and gradually during the next twenty minutes visibility was reduced to three or four hundred yards. The passage of further nuées in the Ambogo valley was indicated by the characteristic rustling noise; the last passed by a little more than an hour after the eruption had begun, at 0700 hours. A dust haze enveloped the area for several hours after activity had ceased. It was 1000 hours before visibility began to improve.

The eruption of 18th February was a protracted multiple event consisting of a series of explosions over a period of more than three hours. The individual outbursts appeared to be discontinuous events and the vertical columns of ash, which rose above the crater, seemed to ascend by billowing rather than by vulcanian projection.

The preliminary crater activity was the reverse of that preceding the 5th March eruption. Gas emission was voluminous and, immediately before the first large explosion, an increase of upper conduit pressures was indicated by the development of a vent at the eastern base of the dome. On the previous day, 17th February, high temperatures had been indicated by a large, strongly billowing cloud which, directly above the dome, was thin and semi-translucent. The next morning at 0630 hours vapour emission was more voluminous and the column rose to over 20,000 feet; a little before 0700 hours it was observed to be coloured with dust which had apparently been produced by small explosions or avalanches. At 0706 hours a small explosion occurred and three minutes later a major earthquake (M.M.5-6) shook the Observation Post.* This earthquake, however, was tectonic and had no obvious effect on the activity of the volcano. Small explosions continued on the eastern side of the dome and low intensity earthquakes of volcanic origin were felt at the Observation Post during the next hour. At 0800 hours an external vent opened on the floor of the avalanche valley near the eastern base of the dome. This unusual indication of increased conduit pressures was the prelude to more powerful activity, and at 0810 a nuée poured from the eastern side of the crater ring and descended the avalanche valley for more than a mile. The form of the eruption cloud indicated that this outburst was confined entirely to the eastern side of the crater and that the nuée distribution was controlled strictly by topography. At 0822 hours a larger outburst produced a more mobile nuée ardente, which split at the base of the avalanche valley, sending its major component down the Ambogo valley (fig. 45). From Andemba village, on the margin of the area devastated by the January eruption, it was evident that the nuée had extended about 4 miles farther down the river valley before it lost momentum (fig. 46). Within the cloud of dust and vapour which rose from the valley and drifted across the northern slopes short bar lightning played continuously, producing an incessant crackling like distant rifle fire. The noise died away gradually as the drifting clouds became more diffuse (fig. 47). An hour later a new phase of activity began and the focus of activity changed to the western side of the crater. At 0933 hours a powerful explosion, appearing to originate from a vent in the western sector of the crater ring, produced a nuée which also descended the avalanche valley and the upper Ambogo. A great column of ash rose slowly above the crater and eventually attained a height of almost 30,000 feet (fig. 48).

* The main movement of this shock lasted about two minutes and the longer period waves were still perceptible four minutes after the shock began. The direction of vibration was initially east-west and later changed suddenly through 90° to north-south. It originated from a focus 200 miles north-west of Lamington.

The column moved up in huge spiral volutes.* This huge pillar of cloud appeared to be essentially a gaseous release; its charge of ash was a secondary feature. A close inspection of the western side of the crater from an aircraft shortly after the photograph of fig. 48 was taken revealed some points of interest. The clouds blanketing the northern slopes resulted from the escape of residual gas from parts of the newly deposited ash beds in the Ambogo and Avalanche valleys—not from the descent of fresh nuées. The expulsion of large nuées had been confined to the early stages, but large-scale activity was still going on in the crater. Behind the western rim the column of rising ash presented an almost straight face which varied in texture from an opaque wall to a thin curtain through which could be seen the woolly convolutions of localized activity. The movement in the column suggested a giant welling-up of superheated gas and ash from many small localized sources rather than a broad pressurized projection of material from the whole crater.

The minor eruption of 11th February appeared to be a good example of the " nuée ardente d'explosion vulcanienne " and it was also an instance of a domal flank explosion which had no effective, if any, oblique component. The outburst originated from a vent midway up the dome flank which faced the gap in the south-eastern sector of the crater wall. The vent had been consistently active during the morning, emitting a cloud of white vapour which was occasionally coloured a yellowish brown by the ejected solid materials (fig. 49). At 1238 hours an explosion produced a nuée which, instead of finding an exit through the south-eastern gap, flowed gravitationally around the base of the dome and entered the avalanche valley through the eastern crater ring (fig. 50). As the nuée moved down the avalanche valley an expanding cloud of ash and vapour rose above the crater and reached an altitude of 27,000 feet in six minutes (fig. 51). The nuée expired after covering three-quarters of a mile along the valley floor, and when the ash clouds cleared the volcano had resumed its normal mild activity. Later in the afternoon, small jets of ash fountained spasmodically from the vent on the south-eastern flank, and at 1800 hours a further explosion produced a vapour cloud which rose high above the volcano. The cloud appeared to be predominantly steam and no nuée was observed on this occasion.

In the few instances where the rate of vertical movement was measured, the vulcanian clouds from the post-climax eruptions ascended at such low velocities that they seemed to have more affinity with the free rise of hot gases than with the upthrusts of vertical projection. According to the estimate of witnesses, the climactic explosion on the morning of 21st January projected its cloud upwards at the rate of 20,000 feet per minute. This estimation does not seem unreasonable for it is less than half the muzzle velocity calculated for Asama volcano by Minakami and considerably less than the velocity, 30,000 feet per minute, attributed to the initial eruption of St. Vincent in 1902 (Williams, 1954). Unfortunately it was not possible to measure the ascent of the cloud from the eruption at Lamington on 5th March, but figures of 3,600 and 3,200 feet per minute for the eruptions of the 11th and 18th February respectively give an indication of the maximum rates for post-climax eruptions. These figures do not greatly exceed the rate of 2,400 feet per minute for the vertical cloud expanding freely from a small nuée (figs. 35 to 38). It is interesting to note that the spear-head projections, which were essentially soundless, low-powered fountainings, had higher velocities, about 4,300 feet per minute, than the larger outbursts which were measured. Turbulence, undoubtedly, is a factor in slowing up vertically

* The column reproduced a pattern of emission which Perret had observed at Vesuvius during the " ash phase " of the 1906 eruption and which he attributed to an obstruction in the throat of the volcano.

rising clouds, but the absence of sound in so many of the eruptions of Lamington suggests that pressures are generally low. Low pressures and an inherent discontinuity of emission are probably the chief factors in determining the low vertical velocities, and both are symptomatic of vulcanian degeneracy. Vertical clouds associated with some outbursts probably resemble true vulcanian explosions in little other than form.

The Nuées Ardentes.

THE AREA OF DEVASTATION.

The nuée ardente from the climactic eruption on Sunday morning, 21st January, was distributed radially in regard to the crater. The hot cloud of fragmental lava completely or partially devastated an area of about 90 square miles. This area consisted of two zones: an inner zone in which lateral velocities were high and consequently devastation was complete; and an outer zone which was subjected more to heat than to mechanical effects. The distribution of these zones is shown in figure 52. It will be noted that the outer zone forms a narrow border to the area of devastation except on the southern and eastern slopes, where topography is uneven.

The influence of topographical control is evident in the general shape of the devastated area and in the characteristics of the marginal zone. The nuée travelled farthest to the north. This was the line of least resistance, the U-shaped crater being open in this direction, and the slopes were not interrupted by any major topographical obstacles. However, even with the crater wall wide open, comparatively minor topographical features immediately below the crater had an important bearing on the distribution of the nuée. Chief among the controlling features was the shape of the avalanche valley.

The higher wall on the western side of the valley had a channelling, or damming, effect which favoured a freer eastern flow of the nuée. In much the same way, the high ridges north of the River Blanche blocked the northerly expansion of Pelée's nuées and favoured their movement south towards St. Pierre in the eruptions of 1902. Thus at Lamington the devastated area is most extensive in the north-eastern quadrant and the confining effect of the western valley wall is quite evident in the corresponding north-western quadrant. The small tongue of devastation which extends east of Issivita village is undoubtedly due to a low gap in the upper western wall of the avalanche valley; this gap gives access to the comparatively smooth surface of the north-western coulée. In its upper part the surface is bounded on its north-eastern side by a prominent ridge which is due to the western extension of the resistant lava flow which is exposed in the wall of the avalanche valley. The gap, in combination with the ridge, provided a channel which directed a part of the nuée effectively to the north-west (fig. 52), and produced the westerly protuberance evident in the early development of the catastrophic nuée (fig. 12).

The nuée did not extend as far on the slopes which lie behind the high crater walls, and its radius decreased from 6-8 miles on the northern sector to 4-5 miles elsewhere. This decrease was due, partly to the less voluminous receipt of fragmental lava, and partly to the broken nature of the country which helped to disperse the laterally moving cloud.

The Inner Zone of Devastation.

Destruction in the inner zone of devastation was almost complete, and it extended without much variation in intensity to abrupt outer margins (fig. 53). The rain-forest on the slopes was flattened (fig. 55) and in some places the earth was swept bare, not even stumps remaining as evidence of the previous forest cover. The completeness of the destruction in this inner zone is illustrated by a photograph of the northern slopes (fig. 56). At Higaturu, 6 miles from the crater, only one house remained reasonably intact. The U-shaped residence of the District Commissioner, in the foreground of the photograph, was pushed fifteen feet northwards and damaged on the southern side by flying debris. Most of the other buildings at the government station were carried away and in most cases only the floors remained. A group of three steel Sydney-Williams huts on the eastern side of the parade ground was badly damaged and had partly collapsed (fig. 57); on the opposite side of the parade ground the superstructure of the District Office was swept away completely.

Throughout this large area of devastation only an occasional tree trunk of the sturdier type withstood the intensity of the avalanche, and where groups of them remained they were invariably protected by some topographical feature.

The Marginal Zone of Devastation.

The marginal area of devastation consisted of a thin heated strip which bordered the abrupt edge of the zone of complete destruction, but its width and characteristics varied considerably. Evidently the velocity of the nuée ardente fell abruptly in the more heavily forested areas and the hot cloud extended merely a short way beyond, scorching and stripping the vegetation. The scorched zone was much wider in the broken country, particularly on the south-eastern slopes. Here the nuée was dispersed and robbed of its mechanical power by major ridges and hills which lay across its path. The sharp dispersal point was marked on the summit of a ridge of which the nuée ascended the near side, sweeping it bare of trees and sometimes topsoil (fig. 54). Then, being given a vertical impulse, it apparently expanded, and rolled back upon itself in great turbulent masses which drifted down over the lower slopes of the volcano, baking the forest beneath it. The hills over wide areas on the southern slopes bristled with dead and damaged trees. Months elapsed before the surviving trees put forth new leaves.

The " steam roller " effect of the descending nuée did not everywhere end abruptly. In some areas the edge of the completely destroyed area was quite ragged as if the front of the nuée were made up of forward-moving jets; in other areas the whole cloud seemed merely to rise slowly. Near the village of Andemba, on the northern slopes, houses and vegetation were irregularly destroyed (fig. 58) throughout a zone of about half a mile, although the hot cloud extended well beyond that point. This destruction was evidently due to high velocity tongues produced by the nuée. The effect was obvious too, in the Sangara Mission village, where trees remained standing adjacent to fallen trees and destroyed houses (fig. 59). The mission residence, situated half a mile closer to the crater and more than a mile below Higaturu, was undamaged except for a few small holes in the fibro-cement wall on the southern side of the building. Even the glass louvre windows were left intact (fig. 60); but on the southern side of the house adjacent store buildings were badly damaged (fig. 61). These buildings certainly helped to break the force of the nuée, but the apparent anomaly in the relative damage to the buildings was probably due more to relative structural strength than to a shielding effect. The force of the nuée was obviously waning, because several nearby trees remained standing and some of them retained branches. The trees of the forest west of Wijo Plantation, on the north-east slopes, were truncated on an ascending scale over a distance of more than half a mile. This effect suggested that the advancing front of the rapidly moving cloud lifted gradually before it stopped. This effect may have been localized by the clearing of the adjacent Wijo area, and consequently less resistance was offered to the movement of a large tongue of the cloud. The lower resistance gave the cloud an additional momentum in this sector so that lateral portions of it over-rode the forest.

DIRECTION OF MOVEMENT.

The orientation of the fallen forest revealed some interesting features of the movement of the great January nuée ardente. Although, broadly, it moved radially from the crater in line with the steepest slope, both topographical obstacles and unrelated turbulence produced local changes of direction. Topographical irregularities on the slopes produced chaotic movements in numerous small pockets; elsewhere broader trends were evident. The influence of the gap and ridge of the western avalanche valley wall has already been mentioned; another example of such a trend is the westward movement of part of the cloud as it left the lower end of the avalanche valley. The movement of the nuée in this direction was determined apparently by a small slope westward towards the main course of the Ambogo valley and more notably by the deflecting effect of the low ridges which formed the eastern wall of the valley. The westward movement of the nuée was cut off by another more vigorous component which descended from the flat-topped north-western coulée (fig. 55).

Some anomalous movements were unrelated specifically to topography and were apparently due to the nuée's tendency to expand laterally in vortex-like forms when a projected tongue was thrust ahead of the main cloud front. An example of such movement occurred south of Higaturu, where a laterally moving jet felled trees against, and at right angles to, the general trend of the fallen forest. From this it may be inferred that a sector of the nuée must have been moving ahead of the main cloud in the lower ground of the Ambogo gorge. From this advancing front a divergent jet sprang out and swung in a curved course across the slope immediately before being engulfed by the main body of the nuée ardente sweeping across Higaturu. A small vortex, formed as a part of the initial movement of this lateral thrust, would explain the falling of a tree towards the crater.

On the margins of the devastated area the nuée evidently became extremely turbulent, and some vortices were developed completely. Apparently, narrow jets had sprung forward from the main body of the cloud and in expanding laterally developed a perfect vortex on either side. Except for the movements induced by obstructing ridges no evidence was found to support Finch's suggestion (1935) that nuées moved in horizontally orientated vortices, but the existence of the vertical vortex was clearly demonstrated.

ABRASIVE ACTION.

Once set in motion, the fluid nuée did not alter its course until compelled by a change of slope which opposed its direction of movement. Where opposition was abrupt, an intensive abrasive action took place and many parts of the slopes showed evidence of its passage by "sand-blasted" and grooved surfaces from which much material had been removed. As a general rule, the zone of marked surface abrasion was confined to a radius of about 2 miles from the crater. The effect of the nuée was greatest immediately below the steeper slopes of the summit nucleus from which it descended, presumably at its highest velocity and fully laden with fragmental lava.

Abrasion appeared most prominently in the area immediately below the avalanche valley. This was the line of least resistance for the nuée; the crater was open on its northern side, and the channel of the avalanche valley below was free of major obstructions. The nuée left the valley as a great torrent of fragmental lava; when it dropped on to the gentler slopes below, the torrent attacked the surface of this new inclination, not only felling the forest and carrying most of it away but grooving and scouring the surface of the ground. In many places the only evidence of the former forest cover was of charred root ends carved off level with the grooved soil surfaces. In explaining the removal of snow below the steeper slopes of Lassen Peak, Day and Allen (1937) do not appear to have appreciated the importance of this mechanism.

Most of the abraded surfaces were shallow scars which were soon obliterated by the normal processes of accelerated erosion. On some small hills, however, the abrasive effect was more lasting and would be easily recognizable for many years after the eruption. The best example of such a feature was seen on a small ridge immediately below the avalanche valley (fig. 62). One side of this hill had been ground to a smooth surface, whereas except for the truncation of the valley heads, the other side retained the surface characteristics of normal erosion. A similar abraded hill is seen in fig. 63. In this instance the hill opposed the movement of the cloud more directly and the remnants of the forest cover are more evident.

The most common frictional effect of the nuée ardente was wide-spread pitting and abrasion of tree trunks; this was a sensitive indicator of variations in nuée intensity. The effect was greatest below the summit nucleus where the slopes were steepest, but even here there was an extraordinary range in the intensity of the phenomena owing to the disrupting and concentrating influence of topography. The length and steepness of a slope seem to be important factors in determining the velocity of a nuée. For example, a stump protruding from the floor of the avalanche valley less than 400 yards from the foot of the dome was abraded much less than a stump at the northern foot of the north-western coulée, about 1½ miles from the crater (figs. 64 and 66). The hammering action of the flying lava seemed even more severe ½ mile down the slope from the base of the coulée (fig. 67), and 2 miles farther on occasional stumps were strongly abraded.

Milder effects were more usual. A tree photographed on a bend of the Ambogo gorge, about 3 miles from the crater, exhibited more typical abrasions (fig. 65). The bark was removed from one side and the surface of the trunk was pitted and lightly charred. In Higaturu, trees were less abraded, although a microscopic examination of a section cut from a steel pole revealed pitting and a shot-blasting effect.*

SPEED.

For the paroxysmal nuées ardentes which overwhelmed St. Pierre in May 1902, Lacroix (1904, p. 267) estimated velocities of about 290 miles per hour by calculating the force required to overturn certain objects. He was strongly of the opinion that

* Appendix I.

even higher velocities obtained, but actual measurement of the speed of the nuées from lesser eruptions gave little support for this contention. He did observe, however, that, over the steeper part of their course, several nuées had velocities greater than 100 miles per hour. Anderson's observation (1908, pp. 493-497) of 72 miles per hour for the nuée of 9th July 1902 is only little higher than Lacroix' estimation of average speed, and is in close agreement with Perret's observation (1937, p. 43) of 74 miles per hour for some of the nuées produced by the activity of Pelée during 1930. Perret states, however, that most of the nuées of this period had a speed of about half this figure and many of them slower.

At Merapi in 1930, Stehn (1935) records velocities of 36 miles per hour for nuées and, surprisingly, 80 miles per hour for rock avalanches. He also noted flows of hot sand which descended the volcano at 14 miles per hour; this rate is in general agreement with that of the pumice flow at Komogatake in 1929 (Kozu, 1934).

The nuée ardente, then, has a considerable range of velocities, and although very high velocities have been suspected for major paroxysms they have not been accurately measured. Unfortunately, no actual measurement of rates of travel was made at Lamington. So far as the catastrophic eruption was concerned the velocity had to be estimated from observed destructive effects and from information supplied by witnesses.

Reconstructing the actions of people who witnessed the climactic explosion roughly limited the period of time from the initial explosion to the incidence of the return wind which rolled the nuée back. This estimate suggested a possible lower limit of five minutes and an upper limit of ten minutes. Assuming that the initial vulcanian explosion lasted three minutes and taking 7 miles as the general distance covered by the nuée on the northern slopes, then the velocity was between 60 and 210 miles per hour.

Comparison of the effects produced by high velocity winds with those produced by the nuée suggests that the lower velocity is more probable. Winds travelling at 50 miles per hour produce appreciable destructive effects; at 60 miles per hour trees are uprooted and considerable structural damage occurs, and at 75 miles per hour destruction is more or less complete (Tannehill, 1938). The damage at Higaturu conformed well with hurricane-force winds, that is, with velocities of the order of 75 miles per hour.

Close examination of the settlement revealed considerable variation in destructive power of the nuée. The southern and western parts of the settlement sustained the most severe damage. At the southern end a few leaning foundation posts were all that remained of some buildings, whole structures having been carried away. On the western side of the settlement, the steel-framed hospital building was completely wrecked (fig. 68), whereas similar structures on the eastern side sustained lighter damage, and one house remained more or less intact (fig. 56). Some of the damage was undoubtedly caused by materials picked up and carried along by the nuée; corrugated iron and planks were scattered over a wide area, and perhaps the stranding of a motor vehicle on top of two truncated trees may be cited as a further instance of the transporting power of the nuée (fig. 69). This incident occurred just below the north-eastern end of the parade ground at the junction of the two northern roads (fig. 56). A comparable phenomenon was demonstrated by a nuée at Mount Pelée which carried a large stone block and impaled it on an iron fence (Lacroix, 1904, p. 265).

Whether such effects can be related to high general velocities is doubtful; they may be caused by local turbulence. At Lamington, movement of the nuée, as indicated by fallen trees, suggests the possibility of turbulence near the suspended vehicle. An easterly trending tongue of the nuée, which may have ended in a vortex, was directed towards the locality, and localized high velocities, typical of a vortex, were indicated by a single instance of the complete stripping of clothing from a body found nearby. Had the general velocity of the nuée been of the order suggested by these examples of its transporting power, the floor plates and assorted debris typical of the remains of most structures would have been carried away (fig. 70).

A mathematical estimate of the velocity of the nuée ardente was made from a study of the deformation of a steel flagpole situated near the hospital (fig. 68) on the western side of Higaturu. The moments of resistance of the steel piping were determined experimentally by Mr. R. Dunning and aerodynamic calculations were made by Mr. A. K. Johnstone and Dr. J. N. Hool.*

Assuming the deformation to have been due solely to air movement, an upper possible limit for the velocity was determined as 160-180 miles per hour. This figure was determined by ignoring, of necessity, the *density* of the cloud and the possibility of an incidental blow from flying debris. Consideration of both these factors would lower this estimate. Another complicating factor in a calculation of this kind is the possibility of stratification in the descending cloud. The nature of the deformation of the flagpole indicated that velocities might increase with distance from the ground, but, again, the possibility of a blow from flying debris cannot be discounted.

Stratified movement as a characteristic of the nuée ardente is strongly suggested by an abrasive effect on the upper slopes of the volcano. Abrasion was noted on top of the north-western coulée during an ascent of the volcano on 31st March, 1951. Ash deposits left by earlier eruptions had filled the major irregularities of the eroded surface of the old flow and had formed a gently sloping hummocky surface which is often a feature of nuée deposits. The passage of a recent small nuée had scooped slight depressions from the tops of innumerable humps covering the slopes. This was the only evidence of the nuée's descent; the valleys between these microcosmic hills showed no signs of abrasion. Unless the nuée bounced from hill to hill, it must have been layered; that is, a low-velocity base which filled the depressions was overridden by a high-velocity layer which abraded the protruding hill tops. A " cushioned " overriding mechanism may account for many of the anomalous velocity effects for which the nuée ardente is notorious.

The overall intensity of destruction undoubtedly gives the best indication of average velocity. If winds of 75 miles per hour can produce almost complete destruction, then an ash-laden nuée, which must have a much higher density, can produce a similar effect at a lower velocity. The upper limit of the time factor suggests the average velocity to have been about 60 miles per hour. Local movements were undoubtedly much faster.

The great ash-flow nuée of the 5th March eruption descended 7½ miles of the Ambogo valley in about 15 minutes. The flow consisted of overriding components, some of which undoubtedly reached higher velocities than 30 miles per hour (fig. 42). At the lower end of its course there were indications that the velocity of the initial flow had dropped to a point where it was incapable of felling small trees (fig. 73). A faster overriding flow evidently had truncated them.

* Appendix I.

TEMPERATURE.

Crater temperature limits have been deduced from the results of laboratory experiments and, apart from Zies's work (1941) on the Santa Maria volcano in Guatemala, no actual measurement of active Pelean crater temperatures has been made. Zies found that the Santiaguito dome was being extruded at temperatures of 700°-725° C. A temperature of the order of 850° C. was indicated by Kozu's experiments (1934) on the lava of Komagatake; Day and Allen's (1925) research on the Lassen Peak lava for the 1914 eruption suggested an upper limit of about 850° C. They also found the Lassen Peak lava to be less refractory than the material from Mount Pelée. This relationship is confirmed by the heat effects produced by their respective nuées ardentes. At Lassen Peak scorching of the vegetation was quite mild and only one fire was started, whereas at Pelée in 1902 nuées started many fires. During their passage through St. Pierre temperatures were locally high enough to melt bottle glass (650°-700° C.) and carbonization of organic material was widespread.

Bright luminous effects were a feature of the strongly extrusive phase of Lamington's activity in 1951. The dome flanks were often covered with cascades of glowing lava and individual parts of the structure were consistently luminous for long periods. The colour of the lava—bright red to orange—suggested higher temperatures than those measured at the Santiaguito dome (700° C.) and the heat effects produced in the nuées ardentes were indicative of much lower temperatures than those prevailing at Mount Pelée in 1902.

The temperature effects of the nuées from Mount Lamington exhibited characteristically erratic distributions which are difficult to explain. These distributions applied not only to the " ash hurricane " nuées, which are largely independent of topographical control, but also to the massive ash flows which descended the valleys. It could be expected, for example, that a tree standing in the avalanche valley less than 400 yards from the crater would be consumed by the descending nuées. In actual fact, such a tree shows only light charring (fig. 64). Other lightly charred, or even uncharred, trees were found below the south-eastern crater rim and also farther down the avalanche valley at the base of its western wall. Turbulence and associated expansion, caused by broken slopes, would tend to lower temperatures in the cloud and inhibit charring effects on many sectors of the summit area of the volcano, but the absence of severe effects in the relatively smooth avalanche valley, so close to the crater, appeared anomalous. The broad coincidence of the zone of severest charring with areas of marked abrasion may supply an answer. The abraded zone which stretched more than a mile below the end of the avalanche valley exhibited the most severe charring apart from the valley ash-flows. The cloud of fragmental lava was evidently compressed into a dense stream which was capable of having a more concentrated effect on exposed surfaces. Further, a rise in temperature may have been induced by adiabatic effects and by the action of trituration and shock which broke up the lava fragments, exposing new hot surfaces and releasing fresh gas.* Some observed effects suggested a re-heating of the whole cloud, as certain trees were deeply charred over their whole surface (fig. 72), and small hills did not offer their usual protection to timber on their lee sides (fig. 63). Charring observed below the north-western coulée (fig. 66) was not nearly so intense as that produced by the more heavily laden cloud descending from the avalanche valley.

* Perret (1937, p. 101) postulates a mechanism of this sort for rejuvenation of the nuée ardente by shock.

The charred zone faded out a little more than a mile below the end of the avalanche valley, and, so far as the catastrophic nuée was concerned, severe temperature effects had ended, although some very lightly charred twigs were seen about a mile south of Higaturu.

The temperatures in Higaturu were not sufficiently high to ignite or char. Fig. 71 illustrates the interior of the remaining house in that settlement. The reel of cotton and the leather drive-belt of the sewing machine were unaffected by heat. The only indication of abnormal temperatures here was the softening and collapse of a plastic lamp-shade suspended from the ceiling above the sewing machine. Deformed plastic objects supplied the best evidence of nuée temperatures at Higaturu and experimental work on such materials suggested a range of temperatures which was related to the duration of the heat. A short duration was suggested by the discovery in the ruins of the hospital of an unopened bottle of ether which had not blown its cork, and an analysis of penicillin found in the hospital proved that it had been subjected to a temperature of 145° C. or greater, for one to two minutes. The most probable temperature deduced from these observations is one of 200° C. lasting for one and one-half minutes. In the marginal village of Andemba less deformed plastic objects were found, although the skin of oranges on a tree nearby was dried out to a thin rind.

The normal thin deposits of ash left by the nuée cooled quickly, and only the massive ashflow deposits which occupied the valleys radiating from the crater retained their high temperature for long. In Higaturu, two days after the January eruption, the temperature at the base of the deepest accumulations of ash was only a few degrees above normal ground temperature. Fires burned for days, however, in the valley deposits and it was common to see towering whirlwinds moving across their surfaces. Similar effects followed the March eruption, which filled the valleys and covered an extensive area of the north-eastern slopes with thick beds of hot ash (fig. 86). Heavy rain eventually cooled these deposits, but in many places only at the surface. For example, it was not unusual to see a log which had been buried for weeks in an ash deposit catch fire suddenly when exposed to air. This occurred in deposits which were undercut by streams swinging across a valley floor. Certain deposits which sealed themselves off from the penetration of groundwater and rainfall were still hot two years after emplacement; in January 1953, vapour rising from a small secondary vent half a mile below the avalanche valley recorded a temperature of 96° C.

Examination of the massive deposits from the March 1951 eruption revealed unexpected irregularities in temperature effects in this relatively coherent flow-type nuée ardente. At Andemba village, the nuée filled the Ambogo valley to a depth of more than 30 feet, and when the deposit was examined an hour and a half after emplacement radiated heat was appreciable, although, in the hazy daylight, the ash was not incandescent. A sample from the edge of the deposit badly scorched, but did not burn, a canvas bag. Numerous half-submerged logs were smouldering on the level surface and, later, many of them were found to be completely carbonized; a mile downstream large green trees were felled when their bases were slowly consumed by the heat from the encompassing ash. Conversely, many trees standing in the deposit were not burnt, and erosion revealed even further erratic temperatures. Small trees standing at the base of the deposit half a mile downstream from Andemba were charred on their tops only (fig. 73). This anomaly could be explained on the assumption that small trees had been buried by an early component of the flow, which was nearing exhaustion both of heat and mobility. A hotter overriding flow charred their tops and burned the larger trees farther downstream. This convenient explanation, however, did not apply to many of the other anomalies observed. In the Banguho River deposits, just outside the devastation limits, some standing trees were quite uncharred although the flow extended at least a mile and a half beyond (fig. 74); adjacent deposits contained numerous logs completely carbonized.

In spite of the greater coherence manifest in this ashflow-type nuée ardente the temperature of large masses of fragmental lava fell below charring level well before they lost their mobility. They thus behaved in much the same way as the paroxysmal nuée.

GAS EMISSION IN THE NUÉES ARDENTES.

Two theories have been put forward to explain both the great mobility of the glowing cloud and the incredibly large volume of gas which expands from it during descent. One theory regards the constituents as solidified; the other considers them partly molten. Lacroix (1904, p. 350) believed the constituents were solidified and were intimately mixed with steam and gas at high temperatures, thus forming an emulsion which was initially under high compression. Anderson and Flett (1903, p. 508), on the other hand, considered that some of the constituents were probably molten and cooled during descent, releasing their dissolved gas. Many investigators have since subscribed to Anderson and Flett's hypothesis and it is now generally accepted that a nuée carries its own gas supply. Perret (1937, p. 84) wrote: "The mobility is due to an immediate subdivision of the lava into discrete particles and the envelopment of the particles in a highly compressed gaseous atmosphere, due largely to continuous vapour emission by the particles themselves". Shepherd and Merwin (1927) reached the same conclusion from laboratory determinations. The gas content of the quickly cooled crust of a breadcrust bomb was found to be unusually high, and this fact, in combination with the gas-emitting vesiculation process observed continuing in the slower-cooling centres of such bombs, led them to the conclusion that intumescence took place in the hot internal environment of the nuée ardente. Macgregor (1938, p. 62), when examining breadcrust bombs from Montserrat, found supporting petrological evidence for Shepherd and Merwin's deduction; the crusts were compact and the centres were porous with a minutely vesicular groundmass. The escaping gases had changed the colour of the residual glass from brown to almost colourless; light-coloured pumices were formed in the same way. Macgregor also drew attention to the inherent porosity of the lava from the West Indian volcanoes and suggested that, during descent, the nuée derived gas both from the highly compressed gas held in the pores of the solidified lava and from the residual molten material in the semi-crystalline lava. In this way, he considered the conflicting views of Lacroix and of Anderson and Flett might be reconciled in some degree.

The abundance of old lava in the nuée deposits at Lamington suggests that a dual mechanism of this type may be necessary to account for the mobility of the avalanche. Examination of the fine ejecta, however, emphasizes the role of the glassy green-hornblende-bearing lava as the most active agent in the volcanic mechanism. It apparently supplied the power for the violent vulcanian explosions of the climactic period, since it was a predominant constituent of the ash that fell at distant places (p. 72). Also, it seemed to preponderate in the ash that fell from the cloud expanding above the nuée of the March eruption (fig. 44). This distribution suggests that the nuée contained a proportion of semi-solidified green hornblende lava which, among the heterogeneous constituents, acted as the chief gas-supplying, leavening agent. The gas-emitting quality of this active lava would give it a special buoyancy and thus explain its abundance in the ash from the expansion cloud.

The freshly deposited nuée material from the March eruption seemed curiously " alive " when examined in the Ambogo valley near Andemba village an hour after its emplacement. A shovel-full of ash flowed easily when tilted and, as it moved, a dozen tiny explosions projected jets of dust a foot into the air. The hot ash was evidently dilated with residual gas and the movement had exposed small pockets of gas or air to sudden heating. As a result they expanded explosively. A similar mechanism, on a large scale, probably contributed to the mobility of the nuée ardente.

Although the nuées lost the great bulk of their gas during their brief descent, some residual gas continued to be emitted after the fragmental lava had come to rest. Much of it undoubtedly escaped slowly through the porous beds without disturbing the surface. In many places, however, emission was brisk enough to form small craterlets which pitted the surface of the deposits (fig. 75). In these small depressions the hot dry dust was agitated continuously by the escaping gas so that it had a movement not unlike boiling liquid. Lacroix observed activity of this type at Pelée and attributed the mechanism to vaporization of sea water which was penetrating the base of the ash bed. The phenomenon at Lamington occurred in flows which had a variety of locations and the mechanism was not dependent on a basal water supply. Its gradual disappearance during the effusive phase of the volcano's activity was attributed to a waning of the inherent gas content of the lava.

DESTRUCTION OF LIFE.

The lethal intensity of the nuée ardente which swept down the mountain on the morning of Sunday, 21st January, can be gauged from the fact that 2,942 people perished in an area where the settlements were small and scattered. Of the 35 Europeans living at Higaturu and Sangara Mission only one emerged from the devastated area; he died that night from shock and severe burns.

Death had been sudden for most people. In the minutes before the cloud reached the lower slopes many snatched up a few possessions and fled. They were overtaken and scores were struck down along the roads leading away from the volcano; they lay where they had fallen. At the Administration School between Higaturu and Sangara Mission 30 or 40 natives crowded into a small house; the nuée swept away the super-structure and exposed the dead occupants piled on the floor of the demolished building. Most of the inhabitants of the marginal villages were struck down in the same way as those in the central zone of devastation, but for small numbers the effects of the cloud were modified to burns of varying intensity. Here, too, occurred survivals, some of which were strangely anomalous.

During the afternoon, when darkness had lifted, 40 survivors from Hamumuta Pinja and Popodota villages found their way into Issivita Mission; many of them were too badly burned to respond to medical attention. Almost the whole of their bodies was burnt; the skin was broken and coming away; it was peeling from some hands like partially removed gloves. In spite of the ministrations of the mission sisters, 22 died before Monday morning. At Popondetta, too, where a dressing station had been set up to receive casualties picked up by a small band of rescue workers who courageously entered the devastated area in their search for survivors, an unknown number of casualties died that day and on the days immediately following. Aircraft were permitted to land on the Popondetta airstrip on the Monday morning and during the next three days 70 casualties were evacuated to hospitals at Lae and Port Moresby. Only three of the evacuees died.

Fig. 53. The abrupt margins of the devastated area on the eastern slopes; undamaged forest in the foreground.

Fig. 54. The nuée has completely destroyed the forest on the near-side of the hill and abruptly dispersed at the summit. Timber still stands on the side farthest from the crater.

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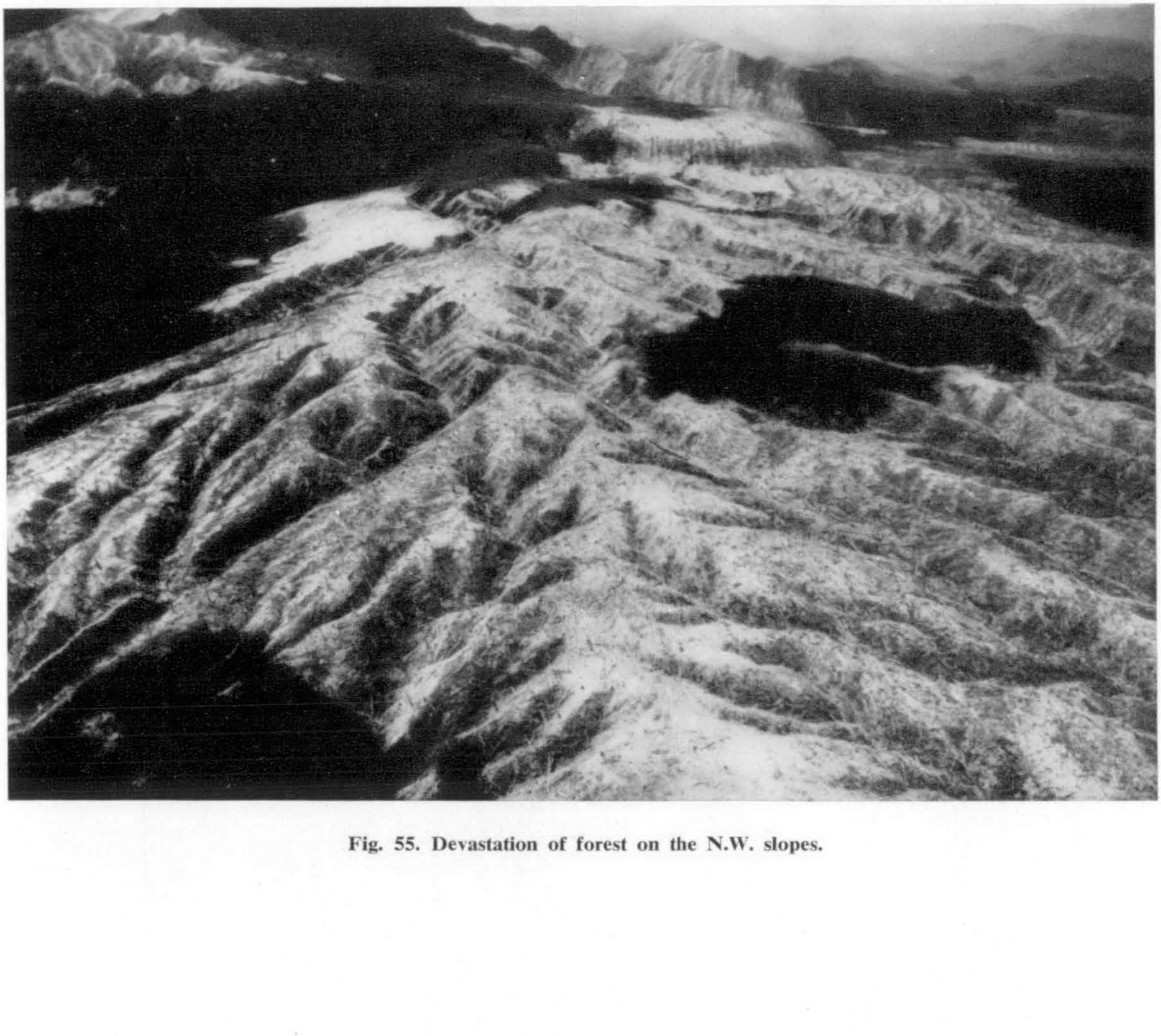

Fig. 55. Devastation of forest on the N.W. slopes.

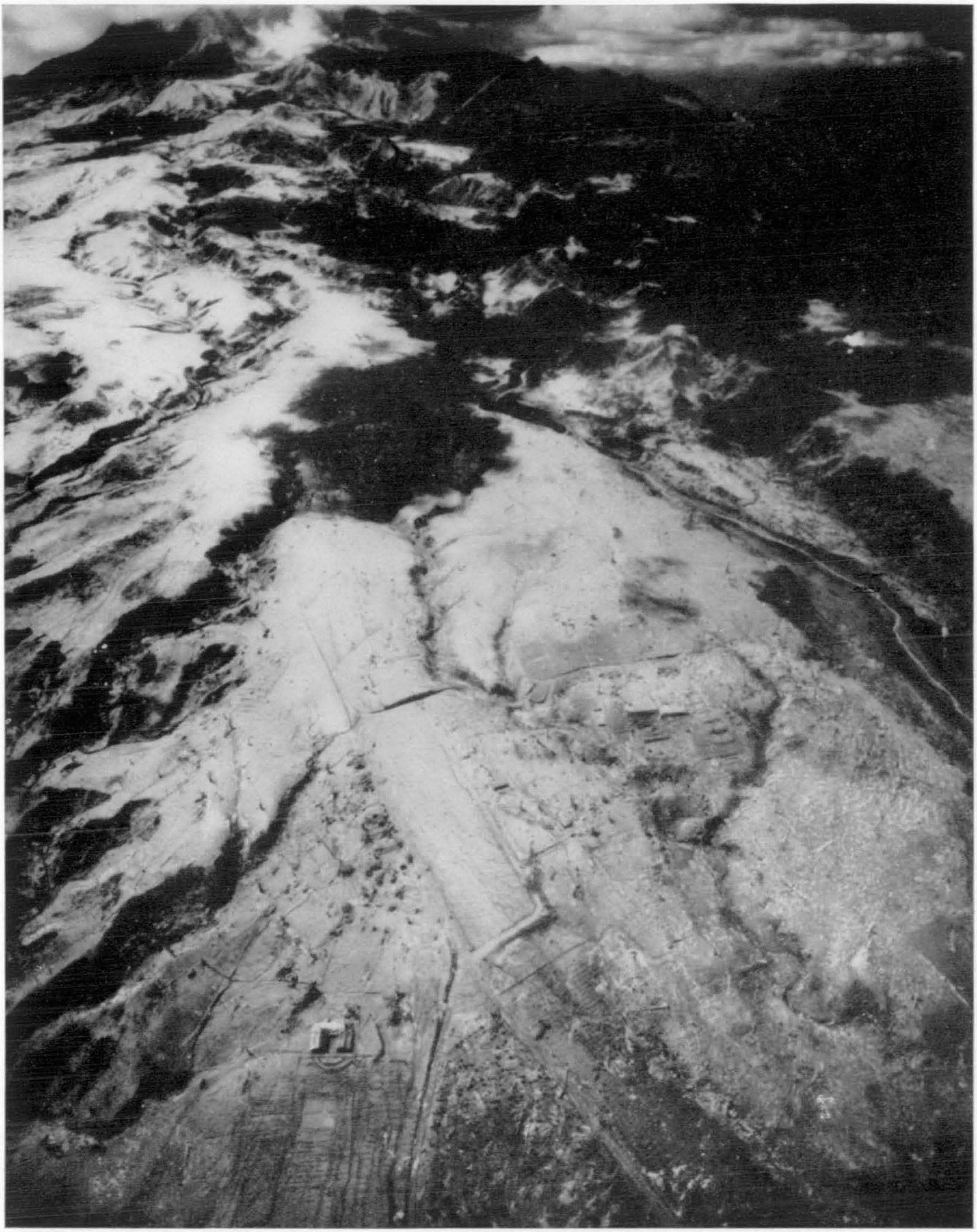

Fig. 56. Devastation of northern slopes. Ruins of Higaturu in foreground.

Fig. 57. Higaturu parade ground and adjacent ruins from the south-west. The platform on the left is the remaining floor of the District Office.

Fig. 58. 23.1.51. Irregular destruction in the marginal village of Andemba.

Fig. 59. Effects of the nuée in Sangara Mission Village.

Fig. 60. Sangara Mission house practically undamaged by the nuée.

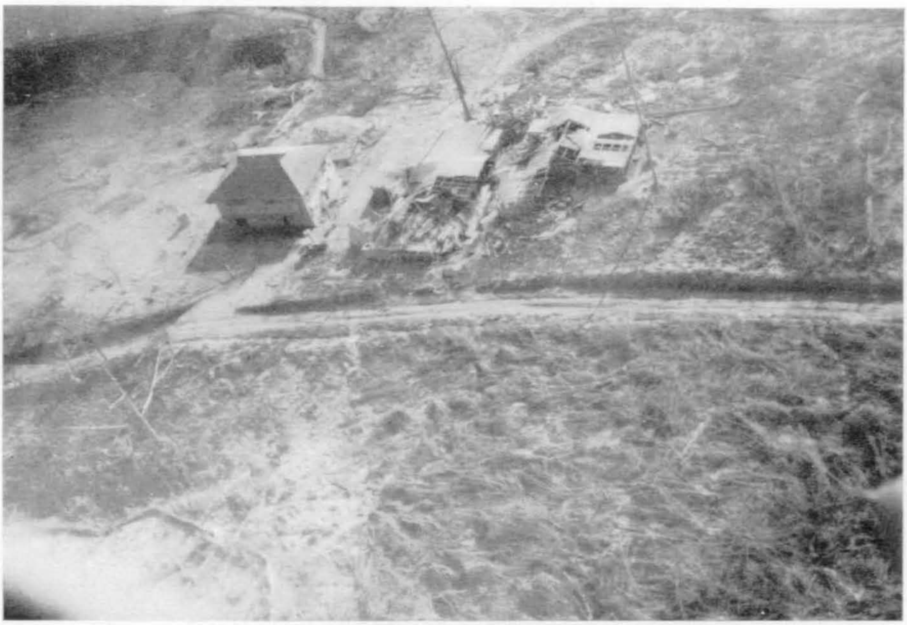

Fig. 61. Badly damaged sheds on the near side of Sangara Mission house.

Fig. 62. Hill below avalanche valley abraded on one side by nuée ardente. Crater lies to right of picture.

Fig. 63. Charred tree-trunks still stand on the leeward side of a small abraded hill.

Fig. 64. A stump in the avalanche valley about 400 yards from the crater shows slight charring and abrasion.

Fig. 65. Bark has been removed from one side of a tree in the Ambogo Valley about 3 miles from the crater.

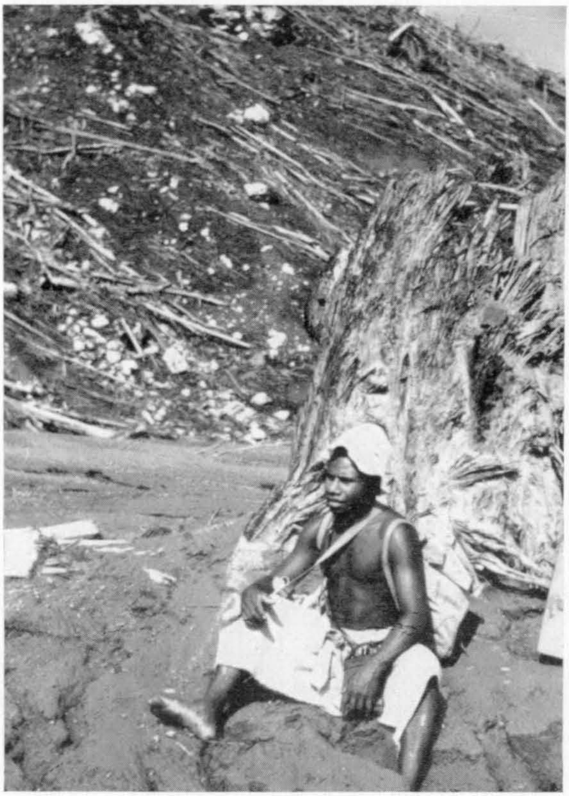

Fig. 66. Abraded and charred stump at the base of north-western coulée.

Fig. 67. Abrasive action of nuée ½ mile below foot of north-western coulée.

Fig. 68. Ruins of hospital building at Higaturu and steel flagpole.

Fig. 69. Motor vehicle suspended on the tops of two truncated trees after the nuée of 21.1.51, northern end of Higaturu.

Fig. 70. Floor plates and assorted debris: all that remains of a house on the north-western side of Higatúru.

Fig. 71. Interior of the remaining house at Higaturu. Note the heavy ash deposit.

Fig. 72. Dec., 1952. A charred tree on the northern slopes about 2 miles from the crater.

Fig. 73. Erosion of March eruption ash beds, 1 mile below Andemba village, exposes tree-stumps charred only on their tops.

Fig. 74. Uncharred tree in ash of Banguho River.

Fig. 75. Residual gas forms small craterlets in ash deposit of 5th March near Coffee Mill.

Fig. 76. 23.1.51. Casualties on Higatura road near Coffee Mill.

Fig. 77. 25.4.52. Scars from burns inflicted by nuée.

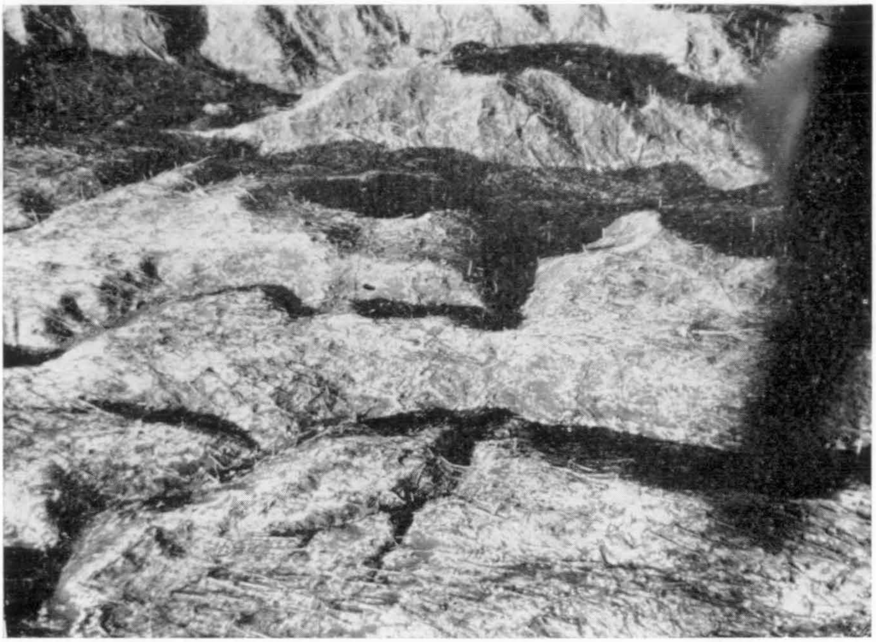

Fig. 78. Jan., 51. Extensive growth of fungus *Neurospora* in devastated area.

Fig. 79. 11.2.51. Taro plants have penetrated the ash near the site of Hupo village.

Fig. 80. Three new branches formed near base of trunk of rubber tree, withered by nuée.

EJECTA DEPOSITED LESS THAN ONE MILE NORTH WEST OF CRATER

Fig. 81

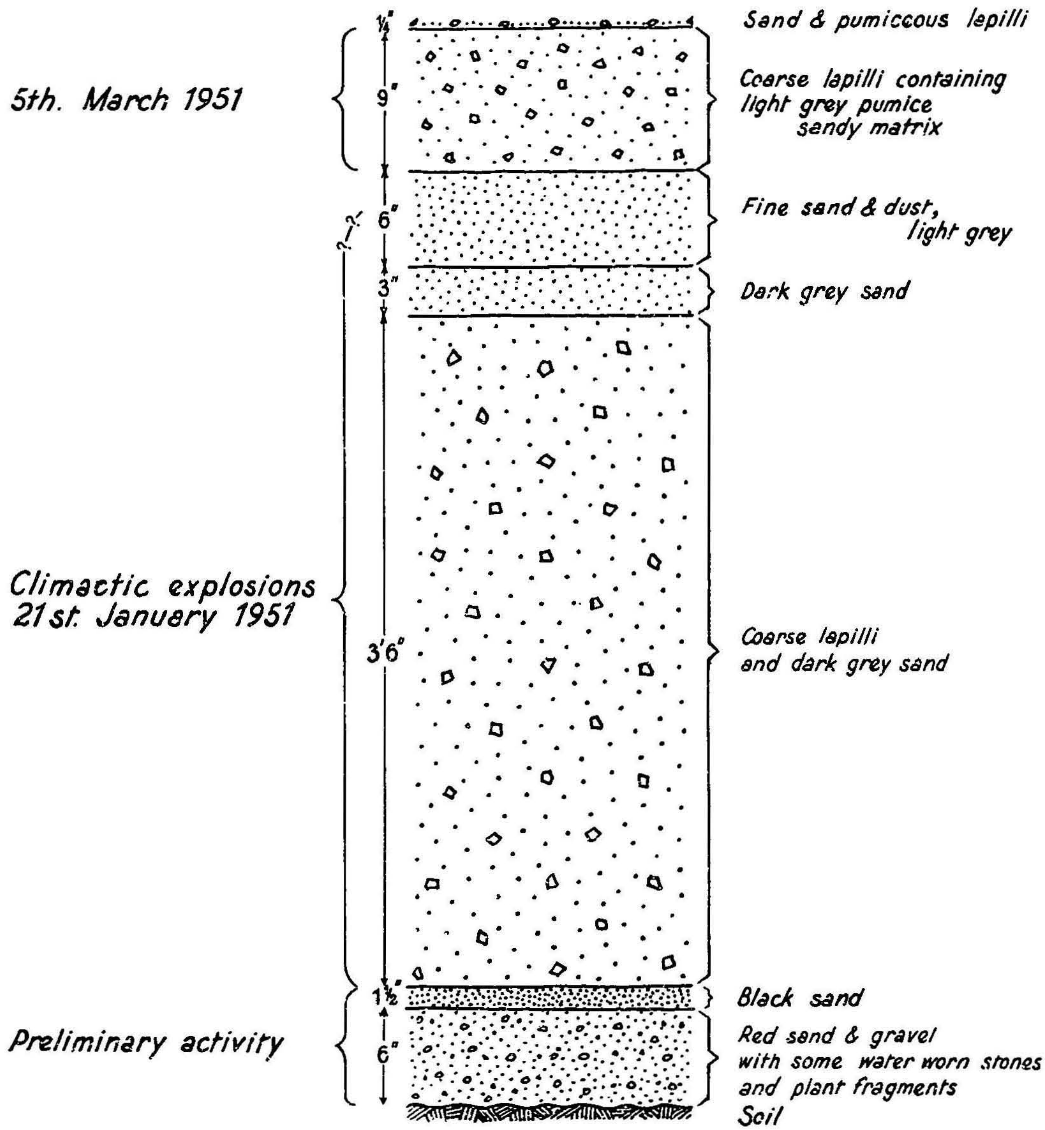

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Fig. 82. 11.2.51. A thin layer of vulcanic ejecta overlies the massive nuée deposit in the lower end of the avalanche valley.

Fig. 83. 23.1.51. Small divergent ash-flow that overflowed from Banguho River near northern edge of devastated area.

Fig. 84. 6.3.51. Vapour rising from the ash-filled valley of the Haijo River.

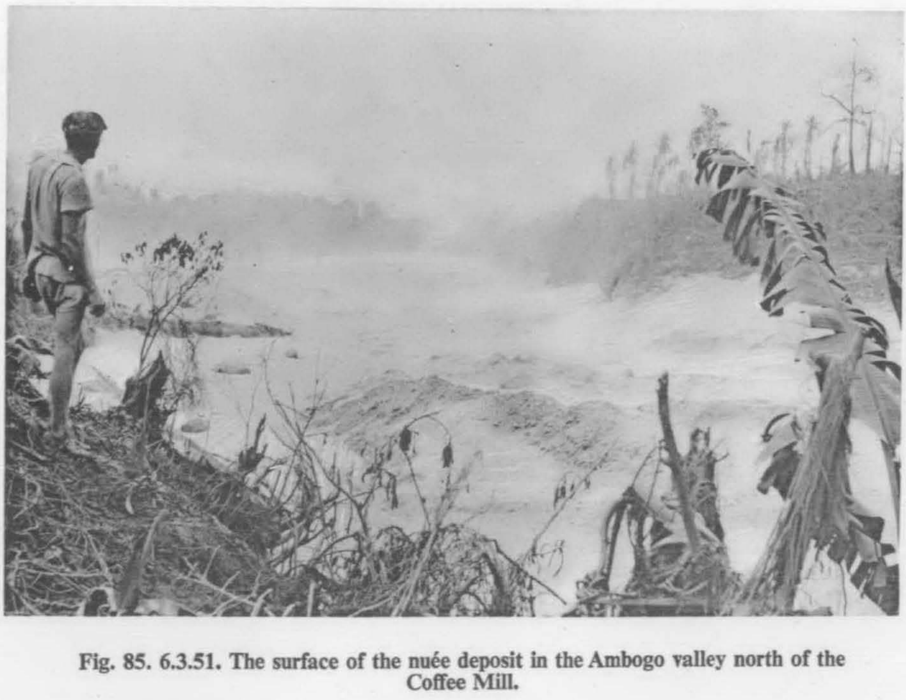


Fig. 85. 6.3.51. The surface of the nuée deposit in the Ambogo valley north of the Coffee Mill.

Fig. 86. Divergent ash-flow on right has drained away from its upper course.

Fig. 87. Dissected nuée deposit of the March eruption in the Ambogo valley between the Coffee Mill and Andemba.

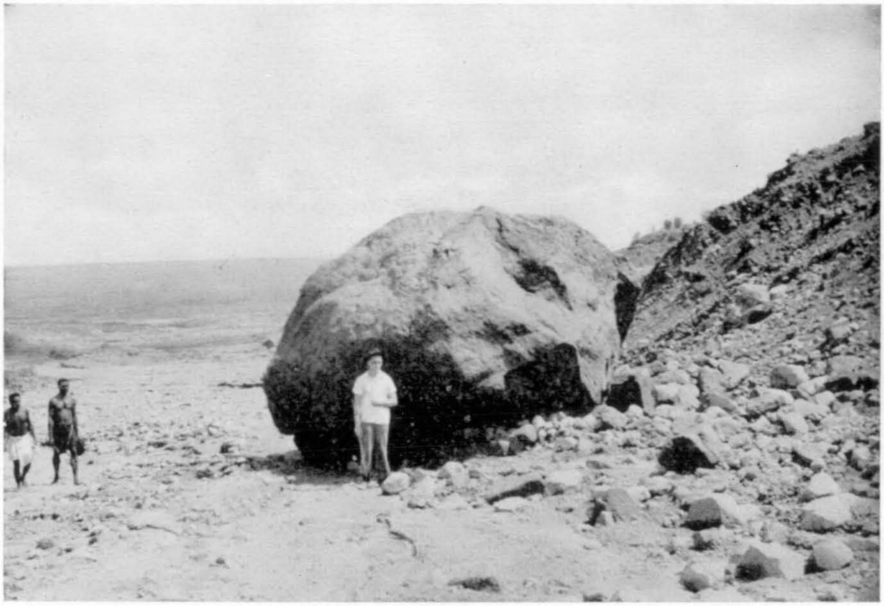


Fig. 88. Block transported more than 2 miles from crater by nuée.

Fig. 89. 11.2.51. Lower end of avalanche valley, looking north-east.

Fig. 90. 11.2.51. Nuée deposits in the upper Banguho River.

Fig. 91. 7.7.51. Nuée deposits in the upper Banguho River.

Fig. 92. Secondary activity caused by a stream undercutting a deposit of hot ash in the Girua valley.

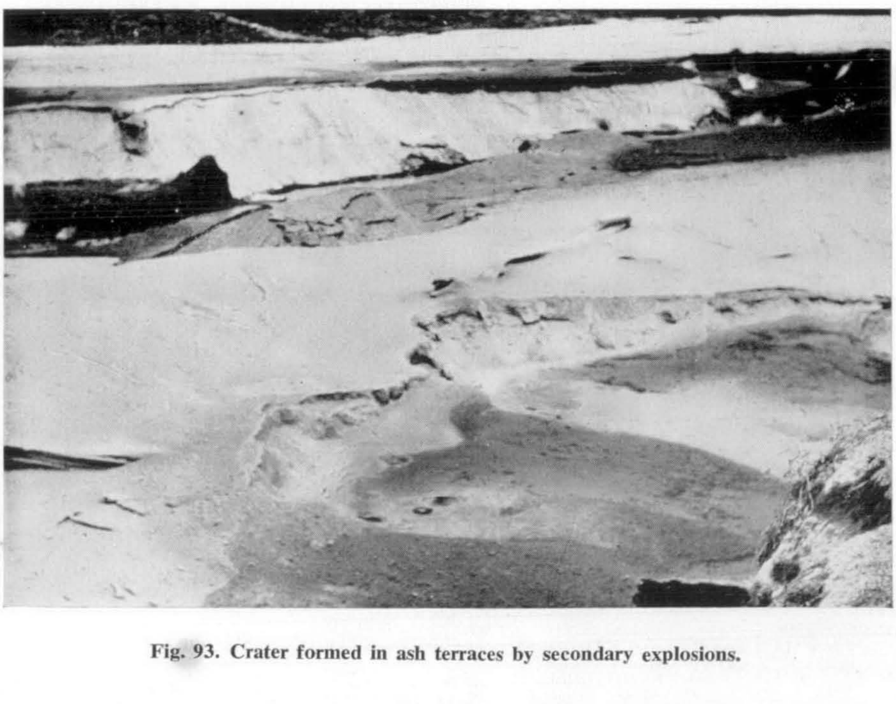


Fig. 93. Crater formed in ash terraces by secondary explosions.

Fig. 94. Hot ash deposit, 30-40 ft. deep, in Ambogo valley near Coffee Mill.

Fig. 95. Violent secondary activity in ash bed after a storm on the mountain.

Fig. 96. 20.3.51. Rapid erosion of Ambogo ash deposit near Coffee Mill. Residual terraces stand 30-40 feet above stream bed.

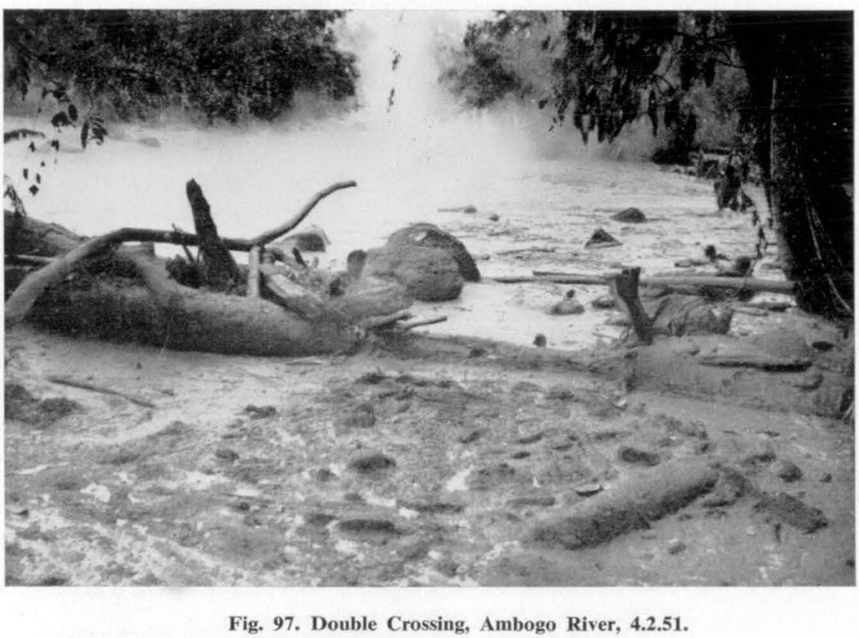


Fig. 97. Double Crossing, Ambogo River, 4.2.51.

Fig. 98. Double Crossing, Ambogo River, 10.2.51.

Fig. 99. Double Crossing, Ambogo River, 23.2.51.

Fig. 100. Double Crossing, Ambogo River, 6.3.51.

Fig. 101. Double Crossing, Ambogo River, 23.5.51.

Fig. 102. Double Crossing, Ambogo River, 18.7.51.

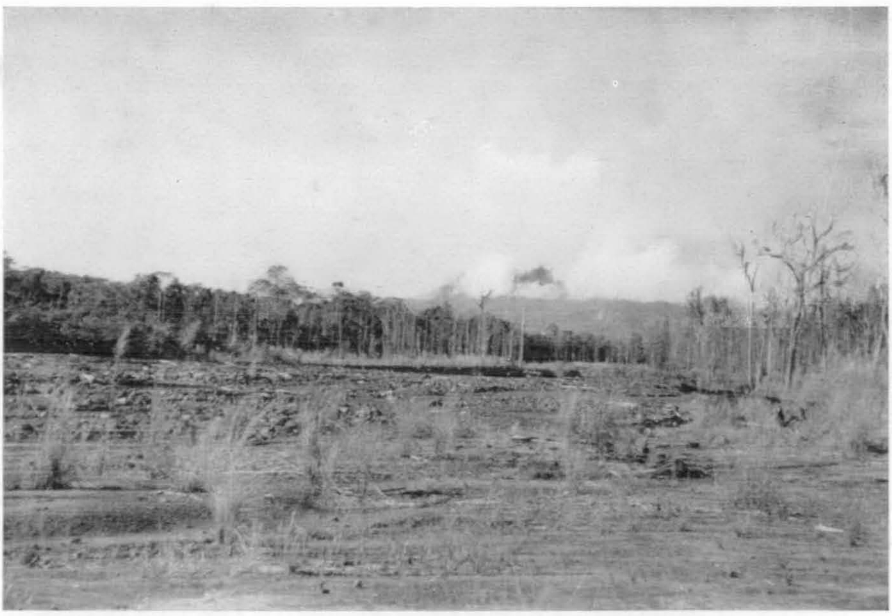


Fig. 103. Double Crossing, Ambogo River, 25.4.52.

Fig. 104. Flooding of Kumusi River and undermining of Wairope Evacuation Camp. The large building on the left of the bridge remnant has partly collapsed.

The exact cause of death in the glowing cloud was, unfortunately, not clarified by autopsy; putrefaction was too advanced when the medical services were free from their urgent obligations to the living. The effects of the glowing cloud suggested that the causes of death were essentially the same as those deduced by Lacroix and by Anderson and Flett for Mt. Pelée and St. Vincent in 1902. At these West Indian eruptions, apart from mechanical battering, the principal cause of death was considered to be steam laden with hot dust. Poisonous gases were not considered an important cause of fatalities. Many who found protection from the main force of the nuée in well-closed rooms survived; those in the open almost invariably perished. The line between life and death was sometimes extremely narrow; in a close group of people one or two occasionally, and inexplicably, survived. Survivors described the symptoms as pains in the mouth, throat and eyes followed by burning sensations in the chest and abdomen, and finally a sensation of rapid suffocation. These marginal cases usually sustained extensive burns on uncovered parts of the body and also internal burns which caused swelling of the mouth and respiratory passages. These victims had an excessive thirst but were unable to swallow, and some suffered acute respiratory distress. Internal damage caused mucous discharge and, not uncommonly, bleeding from the nose and mouth.

Recent investigations of the casualties in the Dellwood fire (Cox and others, 1955) indicated the highly lethal effect of breathing hot air and smoke particles. Although only three of fifteen casualties suffered external burns, thirteen died; post mortem examination revealed swelling, exfoliation, and haemorrhage in the respiratory system. The twelve deaths that occurred within three days of the fire were attributed to " progressive bronchial occlusion, together with pulmonary oedema and infection ". It can be appreciated, then, that the more irritant properties of hot, possibly gas-emitting, lava particles and steam would produce a more severe and immediate effect on the victims enveloped by a glowing cloud.

The appearance of the bodies in the devastated area at Lamington suggested that rapid damage to the respiratory system might have been an important factor in the cause of death. It was extremely difficult to distinguish between Europeans and natives 48 hours after the eruption. This may have been partly due to an intense post-mortem lividity which is characteristic of death from asphyxia. In this form of death the blood does not readily coagulate, but migrates to the extremities of the body. Severe internal burns were suggested by the presence of dried blood around the nose and mouth of some victims. Rigidity was a notable feature of many bodies and was mostly due to the well known effect of heat stiffening brought about by coagulation of the albuminous material in the muscles (fig. 76). In some cases, however, sudden death had caused the instantaneous rigidity characteristic of cadaveric spasm and the bodies remained, after death, in sitting or kneeling positions. Lacroix attributed similar occurrences in St. Pierre to inhibition, a term which describes the depression of the heart's action by stimulation of the vagus nerves. Few people appeared to have been killed by flying debris or by being crushed by falling trees or buildings. There were no dismemberments such as were common in St. Pierre.

A number of observations suggested that, in the marginal areas at least, burns were caused by actual contact with lava particles and not by hot gas. A native woman standing on the road near Amonikiarota village, about ¼ mile inside the limit of the glowing cloud, suffered no burns when she was first enveloped by its forward movement, but when the strong return wind swept the cloud back she was burned on the backs of her arms and legs by the driving particles. Her body was protected by a thin cotton dress; the naked baby she was holding did not survive. The shielding effect of clothing was not uncommon among the casualties and would indicate an explanation for anomalous survivals among furred animals. A small unharmed pup was found in a hollow beneath a fallen tree in Andemba village; a mouse found on the road by the Coffee Mill had apparently been blinded by the hot dust but was otherwise unharmed. Survivals of this sort were also reported at Pelée, where unharmed cats and dogs were found in a closed house in which all the inhabitants were dead (Lacroix, 1904, p. 287).

The experience of one native revealed the narrow margin between life and death and was an example of survival not unlike that of the sailors who were knocked into the harbour at St. Pierre (Lacroix, 1904, p. 289). Watching from the Coffee Mill the native saw the black eruption cloud spreading overhead and suddenly became aware that the cloud was moving along the ground, also. With three companions he ran down into the Ambogo river and stood knee deep in the stream. The nuée knocked him face down into the water with such force that, for a short time, he lay stunned. On regaining consciousness he found that breathing caused a burning constriction in his throat and he plunged his head and body again under the water. When he could hold his breath no longer inhalation filled his mouth with dust but the critical moments of high temperatures had passed. Shortly afterwards, when the intense darkness had lifted, he was able to see that of his three companions only a native woman survived. In spite of extensive superficial burns the two natives were able to leave the devastated area and make their way to Sangara Plantation. The woman subsequently died from her wounds, but the man survived the burns and, like many survivors, carried the scars for a long time (fig. 77).

THE RETURN OF VEGETATION TO THE DEVASTATED AREA.

The first form of vegetable life to appear in the devastated area was a fungus which coloured the surface of the ash with bright orange-yellow patches (fig. 78). The fungus appeared three days after the eruption, after light rain had moistened the ash. It was identified as a " heterothallic species of *Neurospora,* which has been provisionally identified as *N. crassa* . . . The genus *Neuospora* is well known as a troublesome pest of bakeries and similar high temperature situations. The ascospores of this genus do not germinate readily unless subjected for a brief period to high temperatures (for example, half an hour at 60° C.) " (Burges and Chalmers, 1952).

The fungus disappeared gradually over a period of about six weeks and very little of it appeared after later eruptions; small patches were occasionally seen growing on logs which had been buried in the ash flows.

Although the destruction of vegetation seemed, at first, to be complete, many cultivated plants survived. Their survival made an early contribution to the food of the native population, and the coffee and rubber trees may, later, become productive again. The fresh ash boosted, rather than retarded, regrowth of vegetation because in burying the previous vegetation the ash formed a compost which, with the assistance of potassic and phosphoric salts from the fresh ash, accelerated growth. The return of vegetation took place in two phases: firstly, the rapid appearance of root crops in native garden areas, and secondly, the slower establishment of indigenous grasses and secondary forest growth and, at the same time, recovery of trees in the marginal areas.

Five days after the eruption, taro shoots appeared through the ash near the Coffee Mill, and a fortnight later similar plants had penetrated the 9 inches of ash over the gardens north of Hupo village above Higaturu (fig. 79). Within two months the monotonous grey of the devastated areas was broken by many patches of bright green where garden plants such as taro, yams, sweet potatoes and bananas were bursting into luxuriant growth. Although some taro was damaged by the excessive moisture carried by the overlying ash the gardens yielded large quantities of food which the natives used to supplement their diet.

The indigenous plants returned to the area slowly. The grasses came first, spreading gradually from the margins of the devastated area towards the crater. For the first year they remained the dominant vegetation and the slopes remained accessible until early 1952. During 1952, however, when parts of the blanketing ejecta had been removed by erosion from the old soil horizon, the secondary growth quickly became dominant. By the end of 1952 some of the young trees were more than 15 feet high, and access to the crater up the spurs of the mountain could only be gained by laborious cutting of a track through dense vine-entangled thickets and stands of tall cane grasses. The crater area was the last to yield to the invasion of plants, chiefly because the steep slopes had lost most of the original soil cover from which much of the regrowth was springing. However, most of the summit cone had a thin cover of vegetation by early 1953 and, two years later, grasses were beginning to grow on the northern flank of the steaming dome. Probably within 50 years it will be difficult to find signs of the present eruption; the whole mountain may once again be covered with a vegetation that will be indistinguishable from the normal rain forest of the region. The period for recovery of the rain forest vegetation in an area of this type is not known accurately; the process of returning to mature rain forest vegetation possibly involves a time sequence in the establishment of plant types. The establishment of such a time scale would be most useful for identifying and classifying dormant volcanic areas. The Department of Forests has undertaken a study of the post-eruption plant ecology at Mount Lamington, and these data, supplemented by a study of the vegetation around the longer dormant Goropu and Mount Victory volcanoes, should show a useful botanical pattern.

The most unexpected plant survival of the eruption was the recovery of the cultivated trees on the marginal areas of the devastation. Coco-nut trees had been severely scorched and for months showed no sign of life; the trunks of the coffee and rubber trees were withered and stripped of most of their branches. Ultimately, the effect of the nuée ardente on the coffee and rubber trees was the same as a severe pruning; new branches sprouted from their bases and, in the rubber trees, sturdy multiple trunks were developed (fig. 80).

Fragmental Deposits.

Deposits of the Lamington eruption can be divided into three types on the basis of origin, distribution, and thickness. Vulcanian explosions produced widespread and relatively thin deposits; the deposits of the lightly laden " ash hurricane " type of the nuée ardente were less extensive and thicker, and the deposits of the ponderous ash-flow nuées which moved down the valleys were severely localized and massive.

The ejecta from the vulcanian explosions of the climactic periods were distributed widely over an elliptical area with a north-south width of at least 60 miles and a major westerly elongation which, according to reports, extended as far as the mainland of northern Australia. Although the quantity of the ejected material amounted to many millions of tons, the deposits were thin everywhere; even adjacent to the crater on the leeward side this thickness was no more than a few inches. About one-twentieth of an inch of fine material fell around Kairuku, 100 miles west of the volcano, and Port Moresby received a similar fall from the Sunday night eruption. The material was composed mainly of a fine sand which remained a predominant constituent of the deposits even close to the volcano. At the Kumusi River, 13 miles west of the crater, lapilli and small blocks of pumice began to appear in the deposits, and these larger constituents increased in size and number towards the crater. At Issivita, 5 miles north-west of the crater, 4½ inches of ash and lapilli were deposited; south of this point villages received slightly heavier falls of fine material together with pumice blocks up to 5 inches in diameter. On the immediate slopes of the volcano, however, the material from the vulcanian explosions was poorly represented.

A section through the deposits on the north-western coulée, at a point less than a mile from the crater, revealed only a few inches of ejecta identifiable with the vulcanian explosions of the climactic period; except for scattered bombs and large blocks, the bulk of the material had been thrown well beyond the area surrounding the vent (fig. 84).

The " ash hurricane " component of the paroxysmal nuée ardente, as distinct from the " ash flow ", left over the whole of the devastated area a deposit which was thickest close to the volcano. On the northern slopes the marginal thickness was represented by a measurement of 3½ inches near Andemba village; at Higaturu, the average thickness was 6 inches, with local deposits up to 1 foot thick; less than a mile from the crater thicknesses of 3 to 4 feet were recorded (fig. 81). The deposit was composed typically of two distinct layers; at the base, a layer of dark grey sand whose proportion of lapilli and small blocks increased as the distance from the crater decreased; on the top, a layer of light-grey sand, lapilli, and a high proportion of dust which was amassed into pisolites. The upper layer undoubtedly contained both the material falling out of the vulcanian cloud and the fine dust which settled from the expansion cloud of the nuée ardente, and even near the crater the upper layer was only a few inches thick (fig. 82). It was of interest to find that the nuée deposit still contained two distinct layers in locations which were sheltered from vertically falling fragments. For example, in and under houses the dark grey sand was overlain by an equal or greater thickness of the light grey dust, which had a consistency resembling portland cement. This suggested that the paroxysmal nuée consisted of two closely following components, especially as the upper layer, in some instances, was piled against obstacles as if it had been deposited laterally with force.* With the exception of the 5th March eruption, the later nuées did not contribute any substantial quantity of ash to the interfluve deposits on the slopes of the mountain (fig. 81). They were essentially of the ash-flow type and their " ash hurricane " components were evidently lightly laden and rarely extended more than 2 miles from the crater.

The heavier and less gas-charged components of the paroxysmal nuées ardentes drained into the main river valleys around the volcano and formed ash-flows which coursed down the waterways, leaving in their wake massive deposits of fragmental lava. All the main river valleys—the Uno and Indo tributaries of the Mamama on the southern slopes, the Banguho and Haijo rivers on the northern slopes, and the Embara river on the western slopes—contained thick deposits of hot ash after the radial distribution of ejecta from the climactic explosions. The north-eastern slopes below the avalanche valley received the most voluminous flows, which extended to

* N. H. Fisher has pointed out, in discussion, that drifting clouds of fine dust formed similar deposits beneath buildings during the vulcanian eruptions at Rabaul in 1937 and 1941–42.

the limit of the devastated area before they lost their mobility. In their lower courses these flows filled their containing valleys and overflowed into adjacent stream beds to form a broad expanse of hot ash from the margins of which small flows diverged laterally (fig. 83). Subsequent observations of the depths of the valleys of the entrenched streams showed that parts of the deposit were over 50 feet in thickness. Elsewhere on the slopes of the volcano the deposits may not have exceeded 30 feet and, with the exception of the Embara River, ended inside the limits of the devastated area (fig. 52). Only in the Embara valley did the ash flow extend beyond the limits of the " ash hurricane " component of the catastrophic nuée ardente.

The paroxysmal outburst of 5th March disrupted the lava dome and poured a great part of it on to the northern slopes. The heaviest localized deposits of the whole eruption were left by this massive ash flow. On this occasion the Ambogo valley, which had received in its upper valley a relatively small quantity of ash from the catastrophic eruption in January, carried a substantial ash flow beyond the limits of the devastated area to a point 9 miles from the crater. This flow, however, was merely an important subsidiary, since the main bulk of the ash flow swept down the Banguho and Heijo valleys, leaving an enormous deposit spread over the north-eastern slopes (fig. 84 and 86). The ash came down in such volume that it overflowed into many of the adjacent valleys west of the Banguho and, near the margin of the devastated area, flooded an area more than a mile wide. One long tongue continued down the Banguho valley and stopped a short distance above Jegerata village (fig. 52).

When the deposit from this eruption was dissected by the Ambogo river the material was found to be clearly bedded (fig. 87). The constituents of the rapidly successive ash flows produced by this eruption, although unsorted in individual beds, varied sufficiently in size to give them a separate identity. A puzzling feature was a long inclined bedding-plane which appeared inconsistent with the general fluidity exhibited by the flows. The surface of the composite flow was flat in most places, although hummocky and uneven areas appeared where an over-riding flow came to an end (fig. 85). Burial of such an area would have produced a more uneven bedding plane and sharper inclinations than those revealed in the section. A lateral swinging of the flow from side to side of the entrenched valley is the only type of movement which suggests itself as a cause of this feature. Stehn (1935) reported such a movement in a nuée descending the Sonowo valley below Merapi. To preserve this movement in the characteristics of the deposit probably calls for a declining mobility such as that found in an ash flow towards the end of its course.

The deposits from the nuées ardentes contained unsorted fragmental lava whose larger components varied greatly in size. Few boulders larger than 2 feet in diameter were present in the avalanche valley deposits that were examined on the 11th February, 1951 (fig. 82). Most of the lava consisted of dust, sand, and lapilli, and parts of the deposit left by the catastrophic eruption were entirely lacking in large blocks. Deposits in the Ambogo valley, less than a mile below the end of the avalanche valey, contained no large blocks and few components larger than lapilli (fig. 9). Topographical sorting may have played some part in the size of these constituents. The March eruption deposits, on the other hand, contained much material from the disintegration of the dome, and consequently large blocks were common over the whole surface of the great deposit on the north-eastern slopes. One block lying on the surface of the ash deposit in the upper Banguho Valley, about 2 miles from the crater, measured 60 feet x 40 feet x 20 feet and many of the blocks near the end of the avalanche valley were immense (fig. 88).

The absence of large blocks in the deposits on the north-western slopes and, on the northern slopes, the restriction of the coarsest material as a general rule to the valleys clearly demonstrated the sorting action of major topographical obstacles on the constituents of the nuée ardente. This sorting mechanism assumes special importance because its effects have been used as evidence to support the theory that some nuées ardentes are initiated by directed explosions. At Pelée many of the nuées were confined by the valley of the Blanche River which descended from the breach on the south-western side of the crater. When Lacroix (1904, p. 355) found large blocks on spurs and in the valleys immediately south of the Blanche he saw in this distribution evidence for the initiation of the paroxysmal nuées by oblique explosion. At Merapi in Java, however, the nuées sometimes overcame topographical sorting when the stream of fragmental lava flooded over the walls of its confining valley and then subsided, leaving large blocks stranded on the adjacent spurs (Neumann van Padang, 1933, p. 91). Lacroix' theory was criticized on these grounds and in reply he stated that his principal argument for " nuées d'explosion dirigée " was the absence of deposits in the upper Blanche after the first two paroxysmal eruptions of Pelée in May, 1902; the later " nuées d'avalanche " filled the upper Blanche with hot material. Although it is difficult to appreciate the force of Lacroix' argument without an intimate knowledge of the topography, the direction of the upper Blanche, shown on his map, does seem to favour over-riding of the southern wall of the valley below, and it is conceivable that very mobile nuées could drain away from the upper valleys of the volcano. Exceptional mobility would seem to demand abundant fresh lava and high temperature. These properties were characteristic of the lava in the paroxysmal nuées from Mount Pelée.

The Lamington deposits showed ample evidence of the flooding and ebbing of flows in the valleys and there were indications that sustained mobility in an ash flow could remove the flow almost entirely from its upper course. A flood level of the ash flow in the avalanche valley was indicated by marginal terraces, examples of which appeared in the middle and, more prominently, in the lower end of the valley (fig. 89). This feature of flow movement was again illustrated by the large blocks stranded on the walls of the Banguho valley high above the final flow level. The climactic eruption left a substantial deposit of ash in the avalanche valley, and this development, at first sight, seemed to argue against the possibility of more or less complete drainage of ash from the upper Blanche valley at Pelée.

The respective conditions however, differed greatly; the slope of avalanche valley was about 5° compared with 30° for the upper Blanche River, and the Lamington lava contained a high proportion of old material whereas the Pelée lava was almost entirely new. In addition, the higher temperatures prevailing at Pelée would undoubtedly favour a greater mobility. In spite of these limiting conditions at Lamington, however, certain parts of the ash flow from the March eruption left only nominal deposits in the upper parts of their valleys. This was most obvious in the small valleys which took the overflow from the western side of the Banguho. In fig. 86 the ash from one of these small divergent flows has drained away almost completely from its upper course and accumulated deeply towards its lower end. Further confirmation of this trend was given by comparative photographs of the deposits in the upper Banguho valley before and after the March eruption (fig. 90 and 91). Here, below the end of the avalanche valley, only a few feet of material were added to the valley floor in spite of the enormous volume of ash which passed down this channel.

The Lamington deposits, then, draw attention to two volcanic mechanisms which are capable of upsetting the conventional thickening of deposits with proximity to the vent. First, extremely powerful volcanic explosions may eject ash with such force that comparatively little falls near the crater; second, sustained mobility in a nuée ardente may result in the formation of the thickest deposits at points remote from the crater. Whether or not nuée deposits will be thickest near the source vent probably depends on the intensity of the eruption as well as the slope and physical properties of the lava. A series of small nuées under given conditions could conceivably build up a thick deposit near the vent, whereas a large nuée, with its greater heat, gas, and momentum, may drain away from its source. One of the observations at Pelée suggests that even the small nuées retained a high mobility during the early stages of the activity. On the night following the catastrophic eruption of 8th May, 1902, the Abbé Alteroche saw five or six small nuées per minute descending from the crater to the sea (Lacroix, 1904, p. 234); and yet two weeks later Lacroix himself found no hot deposits in the upper Blanche.

SECONDARY ACTIVITY.

The energy of the conduit material ejected by a nuée explosion is not dissipated by powerful scattering in the atmosphere; most of it is stored in the relatively coherent mass of fragmental lava that is poured on to the slopes. Release of the stored energy gives the lava its great mobility, but even when it has come to rest. not all the energy is lost. Immense quantities of heat and some residual gas may be retained in the large deposits left by the more coherent ash-flow, parts of the nuée ardente. The temperatures may be well above incandescence and the cooling rate extremely slow. The residual gas may form high-temperature fumaroles and deposit sublimation products which are indistinguishable from those of the crater vents. Contact between meteoric water and the hot deposits may cause spectacular explosive activity with huge clouds of vapour and dust which can give the illusion of new primary vents opening up on the flanks of the mountain.

When drainage began to re-establish itself in the ash-choked valleys surrounding the volcano, the reaction of the water with the hot ash produced outbursts of activity which, at first, were mistaken for external vents. At 1600 hours on 26th January, 1951, for example, from a point about 4 miles east of the crater, a column of black ash was seen to rise to about 8,000 feet and form a mushroom-shaped head. Bursts of steam and ash from the same point source followed at intervals. It seemed that here was a development for concern—a new vent 4 miles closer to an evacuation camp on the eastern slopes. An air inspection was made without delay. By the time the aircraft had reached the area, the activity had died down to small proportions. The "vent" proved to be in the Girua river valley and the activity was caused by stream action undercutting a bed of hot ash (fig. 92).

Secondary activity became commonplace during the following weeks but it rarely took the form of activity from a single point source. After the March eruption it reached a high intensity; on many occasions widespread secondary explosions enveloped large areas of country with dust clouds and produced visibility conditions similar to those prevailing during a full-scale eruption. These were disturbing periods for those at the Observation Post, for the volcano was completely concealed and it was impossible to tell at the time if a crater eruption was actually in progress. At the same time the loud roar of mudflows descending the Ambogo often drowned all other sounds.

The secondary activity in the Ambogo valley, near the Coffee Mill, provided a fairly typical example of this type of activity. On 20th March, 1951, a storm near the summit of the volcano caused a large volume of water to move down the Ambogo and gave rise to extensive activity along its course. Huge volumes of steam rose above the river valley in billowing convoluted shapes, and explosive jets threw masses of black ash and stones to 200 feet above the river bed (fig. 94 and 95). The river at this stage had cut a narrow channel through the 30-40 foot beds of ash so that it was flanked, on either side, by high terraces, of hot fragmental material. The swinging action of the stream attacked the terrace faces and produced the large volutes of steam. In addition, water penetrated beneath the deposits and on being converted to steam built up pressure pockets which burst through the surface of the deposit as explosive jets loaded with ash and stones. This form of activity formed craters in the surface of the ash terraces (fig. 93).

The phase of intensive secondary activity was short-lived; the streams cut into the loose ash and removed it with extraordinary rapidity (fig. 96). By the end of May the major outbursts of secondary activity had come to an end, but most of the valleys still contained massive residuals of ash. Some were cooled by slowly percolating waters, others had been sealed off by impervious muds and retained their heat for a surprisingly long period. A few vapour-emitting secondary vents were still active at the beginning of 1953, almost two years after the ash had been deposited.

MUDFLOWS AND RIVER FLOODINGS.

Mudflows, which were a characteristic aftermath of the explosive activity, were a natural consequence of increased run-off from the denuded slopes of the volcano and of the great abundance of loose fragmental material. Having overcome the resistance of the accumulated ash in the valleys, the run-off became great rumbling torrents of viscous mud and assorted debris which periodically descended the water-courses, cutting communications, scouring out the valleys, and depositing enormous quantities of material on the lower country.

The action of the mudflows on the entrenched valleys of the upper slopes was demonstrated at Double Crossing where the road to the Observation Post from Popondetta crossed the Ambogo River. The Ambogo, at this point, consisted originally of a small stream embedded in the north side of the valley and only a few yards wide. Above it the branches of the trees of the flanking forest practically joined. Five days after the climactic eruption a small mudflow came down the valley and deposited boulders and mud which closed the Crossing to vehicular traffic. During the next week larger mudflows began to scour the stream bed. They rose with dangerous rapidity, reaching full flood within a few minutes and, at times, advancing down the valley as a wall; some of them were hot viscous* streams, moving at about 10 miles per hour and looking rather like a conveyor belt loaded with logs (fig. 97). Unlike the later roaring, less viscous torrents, their movement was silent apart from the rumbling impact of large boulders, semi-buoyant in the dense stream. The flows rarely lasted longer than an hour or two and subsided rapidly, leaving on the margins of the stream and the adjacent valley floor stranded boulders and a deep layer of mud (fig. 98). Many of the lateral deposits were hot quagmires which were impassable until they cooled and set. The terraces formed in this way consisted of unsorted fragmental material that was indistinguishable from the nuée deposits.

* The relative density of one of these flows was measured as 2.0. This high density accounts for their capacity for transporting immense boulders.

During February 1951, the flows flooded the whole floor of the valley with hot mud, killing part of the covering forest. At the same time the scouring action of these fast-moving flows cut a wide swathe through the forest and formed a broad braided channel which was littered with large boulders carried down by the mud (fig. 99). After the March eruption the daily mudflows ceased for a few days and the end of the inhibiting ash deposit was visible from the Double Crossing (fig. 100). Then a long series of hot mudflows which continued to descend for more than three months extended the devastation along the valley floor (fig. 101). The channel was widened and the heat completed the killing of the marginal forest (fig. 102). By July, 1951, the river had entrenched its braided channel well into the valley floor, the last major change at Double Crossing. In order to keep the Crossing open to vehicular traffic a constant labour force was necessary to cope with the daily changes in the channel floor, but the period of full-scale flooding of the valley was over; by April 1952, grasses were beginning to cover the mudflow terraces above the channel (fig. 63).

At the Observation Post the loud roar of the mudflows moving down the Ambogo valley was heard almost daily during the first half of 1951. Sometimes incidental damming in the upper course of the river produced mudflows of exceptional magnitude, and on these occasions the noise became so loud that many of the local native people became alarmed. The ground vibrations set up by these heavy torrents were recorded on the seismograph as " grass " which, on occasions, had double amplitude of more than a centimetre.

The most serious effect of the mudflows was a rapid silting of the river channels, which increased the danger of flooding. The Administrator of the Territory at that time, Col. J. K. Murray, anticipated the importance of this development when, early in February, he expressed concern over the possible vulnerability to flooding of the Wairopi Evacuation Camp on the bank of the Kumusi River (fig. 52). To assess the likelihood of this suggestion an air inspection of the headwaters of the Kumusi River was made on 8th February 1951, and the camp was seen to be in an extremely vulnerable position. The headwater system consisted of numerous tributaries originating from an extensive area of rugged terrain. A marked increase in rainfall, alone, over this wide and steep catchment area would have been sufficient to cause flooding. Apart from changes in the weather, the main tributary, the Mamama River, was receiving great loads of fragmental material from mudflows, together with the increased run-off from the denuded southern slopes of the volcano. The Mamama also appeared to be partly dammed in narrow parts of its valley where logs brought down from the destroyed forest had piled up in jams. Flash flooding as well as general flooding of the silted lower river course seemed a certain development.

Confirmation of this suggested course of events was not long in coming. The Wairopi Camp was visited during the afternoon and the information on the doubtful safety of the camp site made known. Return to the Observation Post was blocked for two or three hours by a sudden rise in the Kumusi. The road near the Embara crossing was covered by water to a depth of 5 feet. This sudden flood subsided rapidly, but later floods caused considerable loss of equipment at Wairopi before the camp was abandoned. By 19th February the river had broken over its eastern banks and was rapidly undermining the camp site on the western side (fig. 104).

Floods brought about by silting of the river courses and increased run-off did not have serious consequences in other parts of the region, mainly because village sites almost invariably occupied high ground. The one exception was the flooding of a village on the lower Ambogo, where the only serious result was the burial of gardens by mud.

The Dome.

The formation of a lava dome demands a magma of high viscosity whose temperature and volatile content ensure that the rising magma remains plastic in the conduit, and solidifies rapidly on emerging into the crater. These requirements were almost ideally satisfied at Lamington, for the dome which formed in the crater was remarkable for its size and its rate of extrusion. The growth took place in two phases; a rapid uplift during the period of high explosive activity and ending with the partial destruction of the dome by the eruption of 5th March, and a long continued spasmodic growth which increased its height for a year and added to its bulk for a much longer period. The growth of the dome is illustrated graphically in figures 149 and 150, on which are plotted summit heights calculated from alidade readings—and also by photographs showing its development between January 1951 and February 1952 (figs. 105 to 108).

Extrusion of the dome began a few days after the climactic eruption of 21st January, and within six weeks the structure stood more than 1,500 feet above the crater floor. The period of most rapid uplift occurred early in February; between 3rd and 9th of that month the dome was rising at the rate of 100 feet per day. This rate exceeds that of the Santa Maria dome, which recorded 100 metres in a single week (Williams, 1932) and is probably the highest recorded for dome uplift. Rapid movement also succeeded the destructive March eruption but measurements were prevented by poor visibility. Massive spasmodic uplift occurred from mid-May to mid-August, after which, for more than two months, movement was confined to crumbling of the structure, with associated flank avalanches. At the end of October a new phase of movement began, and slow uplift continued until the end of January 1952, when a summit spine reached the terminal height of over 1,900 feet. Spasmodic movement continued throughout 1952 and as a result the dome increased greatly in mass, although the summit of the structure gradually fell to about 1,800 feet. Minor movements followed and in 1955 the structure had the shape of a truncated ellipsoidal cone. The height was about 1,850 feet, the base about 4,500 x 3,000 feet, and the summit about 3,300 x 2,100 feet, giving in all a volume of about one-quarter of a cubic mile (fig. 4).

The Initial Uplift.

This eruption provided a unique opportunity to study the early stages of the formation of a lava dome. Air inspections of the crater, beginning on 23rd January, enabled day-to-day developments to be checked and sometimes photographed, and the open northern face of the crater exposed the interior when the summit was often concealed by cloud.

The extrusive process seemed to begin as a piston-like movement which lifted the whole crater floor several hundred feet above its previous level. Modified from time to time by explosive activity, the shape of the floor changed from a steeply conical funnel through various forms of concavity to a more or less flat platform. The centre of the structure then bulged upwards and gradually developed the convexity of the true dome shape. This change was accompanied by rapid uplift and the growth mechanism which had begun as endogenous became concurrently exogenous. Spines were thrust through the carapace of the structure and their crumbling began to cover the surface of the dome with rubble. During the third week in February the whole central sector of the dome was upthrust in the form of a huge crested ridge. It was elongated north-south and resembled an enormous spine. The sharp crest subsequently thickened as the result of crumbling and further movement. At the end of February further uplift gave the structure the appearance of a new dome emerging from within the old. In the first week of March the rising structure was largely destroyed by powerful explosions.

Thus, in the first six weeks of its growth the Lamington dome temporarily adopted forms which were the final stage in the growth of other domes. At one stage it had the perfect dome shape of Galunggung in Java; later, it had the form of White Mountain in California—" a ridge of debris with a sharp arête " (Williams, 1932), and finally it seemed to have the cylindrical mode of Ousu dome in Japan (Tanakadate, 1929).

To examine these developments in detail the main movements which succeeded the climactic explosions must be traced. When first seen on 23rd January, the crater consisted of a broad, debris-filled depression from the centre of which drifted small vapour clouds. An explosive outburst two days later removed material from the centre of the crater and left a smooth conical depression about 2,000 feet in diameter. The northern side of this depression was bounded by a low rim composed either of extruded or of fragmental materal; on the top of the rim small vents had formed (fig. 109). Within the next 24 hours uplift converted the crater into a shallow parabolic basin which contained one central and two lateral vents of small dimensions. By 28th January, explosions had blasted a steepsided cavity in the floor. A series of curved fractures had developed concentric with the margins of this cavity, and to the south of it a water-filled depression was bounded on the west by a subsidence scarp (fig. 110). The main source of activity was a broad vent, several hundred feet above the floor, in the southern wall. This vent proved to be the most consistently active centre during the whole course of the eruption. On 30th January, the uplifted floor of the crater was almost flat (fig. 111) but parts of it had begun to bulge with upthrusts from depth and a close inspection revealed expansion fractures in the top of the rising northern sector (fig. 112). Further surface fracturing of special interest was evident on the following day; two large arcuate fractures had developed on the western side of the crater and, on the eastern side, innumerable small concentric fractures appeared in the sector of the floor adjacent to a lake (figs. 113 and 114). This pattern of movement seemed to demonstrate that upthrusts under such conditions may produce concentric and arcuate, rather than radial, fractures.

The extrusion process accelerated early in February; by 3rd February the central area was being thrust above the level of the old northern lip, which was composed of darker coloured, cooler material than the centre (fig. 115). The uplift was to some extent differential, being most pronounced in the southern sector of the crater where the main vents were located. In the southern crater ring, or trough, two vent groups were active, one of which was immediately south and the other south-west of the dome; on the dome itself, a large vent on the southern margin, shown in figure 109, was the major centre of gas emission. Three minor vents were active on the northern summit of the dome.

The vent on the southern sector of the dome became extremely active during the next few days of increasing explosive activity (fig. 116), and as a result the first spine to emerge from the dome was rarely visible in its initial stages of growth. Confined as they were to the southern sector of the dome, both the explosive and extrusive processes were closely associated in time and place, thus repeating a pattern which seems to be a rule in eruptions of the Pelean type. At Pelée, Lacroix drew attention to the upthrusts of the great spine after explosive outbursts which originated near its base. This close association was repeated several times at Lamington when the gas tension in the lava was high.

On 5th February, the sharp spine was barely visible at the base of the billowing clouds of dust and vapour which were rising from the southern vents (fig. 117). As growth continued the spine crumbled rapidly and covered the relatively fine material of the dome surface with a coarse rubble containing large blocks. This exogenous growth was confined for several days to the southern sector of the dome. In the meantime, the northern sector had been growing prodigiously and rounding out its symmetry of form by internal expansion (fig. 118). The slopes in this sector remained remarkably smooth and uniform in spite of upward growth and expansion northwards down the avalanche valley. This was because they were composed of loose fragmental debris which adjusted itself from time to time by small slides. The hot, light-coloured material revealed by these movements gave the surface a mottled appearance, and on 8th February a thin ribbon of hot ash descended from the summit near the small northern vents to the foot of the dome (fig. 119).

A ground inspection of the crater was made on 11th February. The northern face was found to be composed of rock debris of a texture almost identical with that of the nuée deposit in the avalanche valley (figs. 120 and 82). This suggested that the rising dome was covered by a mantle of conduit debris. While the party was standing at the base of the dome a strong earthquake shook the crater and precipitated several noisy avalanches down the flanks of the dome. These falls of inert material were small and ended at the foot of the dome; they had none of the fluidity of the hot, gas-dilated avalanches which later became a feature of dome movement.

By 10th February, differential movement in the dome had formed an arcuate ridge which extended north from the western edge of the spine and continued in a curve ending at the north-eastern margin of the dome (fig. 121). This delimited a sector, comprising the south-east, and part of the north-east, quadrants, which at this stage of its development was already exhibiting features which suggested that it had a separate identity. Generally, its uplift was lagging behind that of the remainder of the dome, and at the same time it contained two distinct elements indicative of a highly active magma. These were a rising spine at its southern end and an ash-emitting explosive vent near its centre. Later developments further emphasized the high activity potential of the magma in this sector of the dome, and although the individuality of the sector was engulfed from time to time by large-scale spasms of crater activity it repeatedly asserted its identity in both explosive and extrusive activity. The eruptions of 11th and 18th February and of 5th March originated largely from this sector of the dome and a rapid extrusion of this eastern part of the dome preceded and followed the latter eruption. Specimens eventually collected from the eastern side of the dome were found to have a more porous texture than those from other parts of the structure, thus confirming, lithologically, the distinctive nature of this sector of the dome.

The rise in seismic activity and the eruption of the 18th February were accompanied by a major dome movement. The structure seemed to behave as a homogeneous unit when a huge mass of rock began to emerge as if the whole core were being extruded. The bare rock faces on the eastern and western flanks of the core suggested that it was monolithic. The rough crest added to the illusion of a giant spine. Talus from the crumbling summit of the structure began to cover the hot eastern and western flanks, but no falls occurred on the northern flank where the dark-coloured cold material seemed to cling to the rising centre to form a semi-conical apron (fig. 122). With further uplift the centre broke away from the northern apron and a small depression formed between them. In the meantime, further extrusion and the collapse of numerous small spines had thickened the crest of the dome. Debris produced in this way filled the depressions in the structure and it became shaped like a truncated cone (fig. 123).

At the end of February, a massive uplift of the dome was the preliminary event leading to the destructive eruption. Once again the centre of the structure seemed to be extruded, this time more or less cylindrically. As the movement proceeded, numerous avalanches descended into the flanking troughs, and after a rise in seismic activity on 2nd March these became more numerous on the eastern and north-eastern flanks. This was due to the concentration of extrusion forces in the eastern sectors of the dome. Immediately before the culminating eruption the dome became asymmetrical in profile with the whole summit area sloping up to a high eastern shoulder.

Explosive Destruction.

The paroxysmal eruption of 5th March shattered the dome, and two-thirds of it was removed in nuées ardentes which descended the northern slopes. The remnant consisted of a ragged elongate ridge, the apex of which was west of the centre of the crater. The effect of the explosion can be envisaged if this remnant is regarded as the core of a roughly cylindrical plug which was disrupted by explosions on its northern, eastern and southern flanks. The explosion had been most powerful on the eastern side, where it removed both the talus apron and part of the adjacent plug. On the northern flank all the talus had been removed and a plastic section of the dome which had overlapped the northern rim had been truncated (fig. 124). The talus apron and part of the plug had similarly been removed on the south-eastern side, suggesting that the structure had been cut back to the crater vent limit indicated by early observations (fig. 113). The flank explosions did not extend to the south-western and western side, for here the talus apron remained relatively intact. The original limits of the dome were delineated on the south-eastern and northern sides by a ridge which represented the remaining base of the old talus apron (fig. 125).

Regrowth:

Rapid uplift followed this destructive eruption as further extrusion began to repair the most damaged sectors. The appearance of ash-emitting vents in the eastern and south-eastern sectors indicated that the rising magma still retained a relatively high volatile content. In fact, a small unobserved eruption occurred later in March, for at the end of the month evidence of a recent nuée was found on the western slopes. This outburst had no apparent effect on the regrowth of the dome, and within a month of its destruction it had recovered much of its previous bulk and had developed an asymmetrical profile similar to that preceding the destructive eruption (fig. 126). It seems probable though that the uplift beginning in late February, the explosive destruction, and the regrowth were all due to a single sustained pulse of volcanic energy originating from a specific sector of the crater.

The subsequent growth of the dome continued spasmodically, and irregular pulses of extrusive energy were confined for protracted periods to specific sectors of the structure (fig. 154). The eastern sector became stable early in April as the western sector began to rise. Movement was slight and spasmodic until mid-May, when a major spasm lifted this sector to a greater height than that of the dome before the destructive eruption. Spasmodic uplift continued in this sector until July, when the focus of extrusion changed first to the northern sector and then to the centre. Throughout the remainder of the year the movement was confined predominantly to the central sector except for a short reversion to the eastern sector at the end of October. Despite occasional small uplifts after January 1952, the disintegration of the terminal structure exceeded the extrusion rate and the height of the structure declined.

The Mode of Extrusion.

During the initial stages of growth, when abundant volcanic energy was available, the dome was extruded more or less as a monolithic unit from the full width of the conduit. This unified movement persisted almost up to the time of the destructive March eruption. Before the end of this early growth, however, differential movement indicated a trend towards a piecemeal development of the structure. After the March eruption the movement became entirely piecemeal and only one part of the dome moved at a time. It is interesting to speculate whether this behaviour can be explained in terms of a conduit system made up of separate vents. Perret (1937, page 112) drew attention to the relative permanence of individual crater vents or fissures and has provided an instance of the extrusion of elevated structures above them. To enlarge on this observation and postulate pre-existing and separately functioning vents as an explanation of the piecemeal development seems inadequate because the concept must explain why one vent functions at a time and why the final structure erected over the conduit has an essential symmetry. An obvious unity exists both in the intrusive mechanism and the extrusive product.

The key to the problem seems to lie in the observation that the piecemeal pattern of development became firmly established at the end of the paroxysmal phase of the volcano's activity. It is suggested that the extrusive activity became localized when the volcanic energy had dropped to a level at which it was incapable of maintaining the whole conduit in a state of mobility. Only sufficient energy was available to maintain a localized channel of escape for the conduit magma. Thus, in the lava-filled conduit we have a mobile zone which, if we accept Perret's generalizations concerning the inherently vertical nature of magma movements, can be regarded as a vertical gas-fluxed chimney. The dimensions of this lava-filled chimney will be dependent on the abundance of emanations and on the gas-charged magma ascending from depth; the location seems to be partly determined by the resistance of the crater lava and partly by the cooling pattern of the conduit lava. Hence, first we have growth which changes from side to side of the dome in accordance with the pressure of the overlying summit structure and finally its migration towards the centre of the conduit as the activity declines and the margins cool.

Post-destruction movement became focussed on the eastern side of the dome, where explosive disintegration has been greatest and the pressures of overlying lava were least. Once movement had been established in this zone it persisted beyond the point of achieving equilibrium in the height of the structure elevated above the old crater floor, and a broad peak was formed on the eastern side of the crater (fig. 126).

The persistence of movement is probably due to a natural momentum gained by concentrating the hotter elements of the conduit into one mobile zone and at the same time allowing the carapace elsewhere to thicken and become more resistant. By the end of March the south-east sector had been lifted to a height comparable with that reached before the eruption. Its lateral growth stopped short of the basal rim left by the margin of the earlier dome (fig. 127). Dark streaks on the slope indicated that temperatures were falling, and shortly afterwards the whole of the eastern sector cooled rapidly and the focus of extrusion changed to the west.

Changes in local temperatures and fluctuations in gas emission, together with a change of the origin of emission and widespread disturbance of the whole dome, introduced the transfer of extrusion focus from the east to the west of the dome. The orange-red glow of incandescent lava gradually became more pronounced on the western side of the dome during the third week of March, and by the beginning of April this flank glowed more brightly than any other part of the dome. During the same period the western side of the dome also became the main source of gas emission and the volume of the crater cloud fluctuated markedly. On 19th March the vapour column rose thousands of feet above the volcano and then as a prelude to more vigorous emission activity declined to a low ebb. Even the relatively constant vent in the south trough almost closed. An abrupt increase in gas emission signalled the arrival of the pressure pulse which ultimately established a new channel for lava movement in the western side of the conduit. Escaping gas rose 20,000 feet on 23rd March and small geyser-like explosions were bursting from the floor of the south trough. New material on the dome slopes and ash-flow paths in the avalanche valley indicated widespread dome movement. The following day revealed more pronounced movement; an upthrust of the whole protrusion was suggested by the development of a ledge half-way up the north flank of the dome. This ledge was at a level conformable with similar but broader ledges on the western and southern flanks of the structure. The effect resembled that of a cylinder emerging slowly from the talus-covered flanks. Although the height of the dome had decreased by 40 feet since the previous day it was possible that the whole plug moved up, because the spasmodic descent of great sheets of debris from the whole dome surface suggested that crumbling of the superstructure was unusually severe.*

After this broad movement activity became concentrated on the western sector. The zone fissured, fractured, and crumbled, and many new vents became active; some of them emitted clouds of red-brown dust. Crater activity declined towards the end of March. On 4th April a new extrusive pulse was announced by a phenomenal increase in gas emission which may have been explosively initiated. Major uplift in the western sector followed and a large spine rose above it. Within a few days avalanches from the crumbling of the new extrusion were overlapping the basal remnant of the original dome in the north-western flank (fig. 128 and 129). A new lava channel on the western side of the conduit seemed now to have broken through its restricting cover.

During the next three months extrusion was confined almost entirely to the western sector and by early May the structure had the appearance of twin domes (fig. 130). The eastern side was cold and static and the light colour of the western sector indicated heat and mobility. The new structure grew largely by solid extrusion.† A series of ragged spines, some of large dimensions, rose and collapsed on the western summit area. This persistent local spine growth resembled movements of the Mount Pelée dome during the growth and collapse of the great spine of 1902-1903. It was fitting, therefore, that the culminating point of the growth in the western sector should produce a distinctive spine.

* The distinctive ledges on the northern and western flanks were soon engulfed by the debris from further movements, but on the southern side a broad terrace formed, and remained a permanent feature of the southern sector of the dome despite later movements.

† One observation of the movement suggested that the whole of the western side of the plug was moving up at least during the latter part of April.

This unusual "hog-backed" structure rose about 300 feet above the dome in June (fig. 131). A broad squat version of the familiar half-horn spine, it was smoothly convex on the eastern side facing the centre of the dome, and steep and ragged on the western side (figs. 132 and 133). From the west the profile had the appearance of a slightly flattened half-circle (fig. 134); thus, the protrusion had roughly the shape of half a hemisphere and had a diameter of 800-1,000 feet. It seemed that this exemplified perfectly Perret's observations (1937, p. 117): "A complete spine . . . is, so to speak, a more mature dome, a more complete monolithic structure. This is not generally recognized because only a portion of the larger spines usually rises above the surface; the remainder is left below. What is actually seen is a vertical section of the whole, generally half, with a flat inner face and rounded back". It appeared that the end phase of the activity from the western channel in the conduit had provided a spine of such dimensions that it could be considered as part of a subsidiary dome.

A new plasticity of the internal lava was indicated by the great rounded back of the western spine. All the earlier large spines and most of the small ones had consisted of blocks without evidence of plastic deformation; small half-horn-shaped spines had been seen on rare occasions. This evidence on a large scale of a change in the physical condition of the conduit was a significant development soon to be followed by new activity and a change in the mode of growth.

Earthquake swarms towards the end of June indicated movement at depth, and at the end of the month a vent opened in the centre of the dome. A brief spasm of the mild explosive activity was followed by vastly increased gas emission, which was undoubtedly associated with the accession from depth of new magma. This magma evidently had an added mobility, for it broke through the northern flank of the dome and formed a lateral structure which extended the northerly base by about 300 yards during July (fig. 135). This northern structure can be regarded either as an extremely thick and viscous flow or as an expanding dome flank which overlapped the northern rim of the conduit. Although originally it rose in height as though being thrust up in the same manner as other sectors of the dome, it soon developed a flat ledge-like shape which differentiated it from the higher mass behind it. The fact that large spines did not develop from the new sector and the absence of abundant gas emission indicated that it was outside the orbit of the conduit and essentially a flow overlapping the avalanche valley. It was easy to overlook this point later when debris from the sector spread across the whole width of the avalanche valley (fig. 136). Eventually with further development of the dome the northern flank lost its separate identity by becoming an integral part of the huge central protrusion (fig. 140).

The growth of the northern side of the dome was inseparable from movement in the centre. The northern extrusion began after both explosive activity and movement in the central area of the dome, and its end phase also was accompanied by concurrent extrusion from the centre. Both movements apparently were due to a rise of magma in the central part of the conduit. The new magma had broken out first on the weak northern flank and, when sufficient reinforcement was offered by the northern increment, movement was resumed at the centre. The central extrusion took the form of a single spine which was first seen amidst the swirling vapour of the dome on 19th August (fig. 137) four days after renewed movement in this zone had been indicated by avalanches.

Fig. 105. Growth of the dome, 30.1.51.

Fig. 106. Growth of the dome, 30.3.51.

[*To face page* 64.]

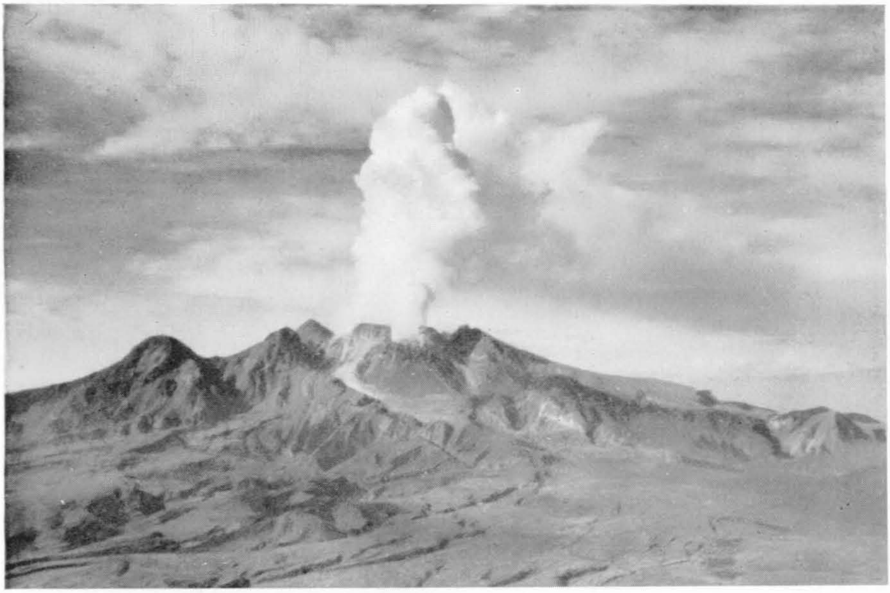


Fig. 107. Growth of the dome, 29.11.51.

Fig. 108. Growth of the dome, 13.2.52.

Fig. 109. 26.1.51. Small active vents on raised rim formed across open side of crater.

Fig. 110. 28.1.51. Southern sector of crater floor as seen through south-eastern notch.

Fig. 111. 30.1.51. Uplifted crater floor, from NE.

Fig. 112. 30.1.51. Closer view from NW reveals differential nature of uplift and fracture development in crater floor.

Fig. 113. 31.1.51. Eastern side of crater floor; small concentric fractures.

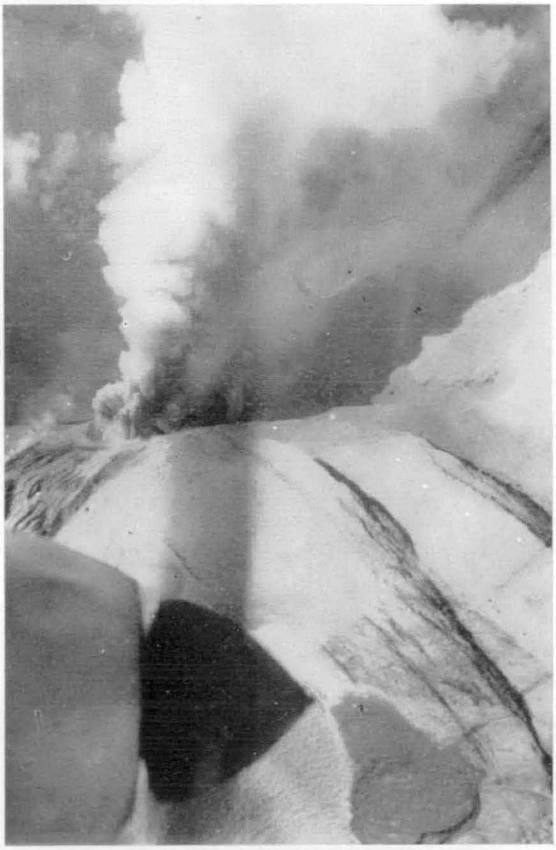


Fig. 114. 31.1.51. Western side of crater floor; large arcuate fractures.

Fig. 115. 3.2.51. Rapid upthrust of central sector of dome.

Fig. 116. 5.2.51. Increasing explosive activity from southern vents of dome.

Fig. 117. 5.2.51. First spine appears on southern sector of crater.

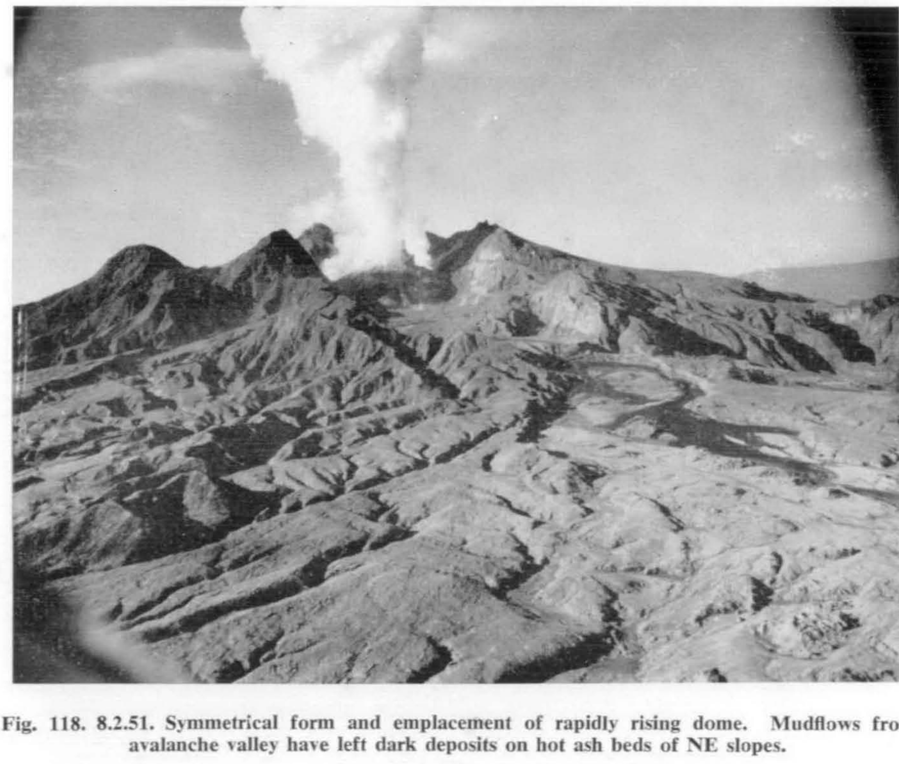


Fig. 118. 8.2.51. Symmetrical form and emplacement of rapidly rising dome. Mudflows from avalanche valley have left dark deposits on hot ash beds of NE slopes.

Fig. 119. 8.2.51. Small slides of hot debris on northern and eastern flanks of dome.

Fig. 120. 11.2.51. Debris mantle at northern base of dome (cf. Fig. 83).

Fig. 121. 10.2.51. Rising spine and active vent in south-eastern sector of dome.

Fig 122. 20.2.51. Cold talus apron clinging to northern end of rising crest of dome.

Fig. 123. 24.2.51. Truncated cone shape of rising dome.

Fig. 124. 12.3.51. Rapid regrowth of destroyed dome is under way.

Fig. 125. 15.3.51. Eastern flank of dome, showing basal rim of old dome in background.

Fig. 126. Early April, 1951 Asymmetrical regrowth of dome after destructive eruption.

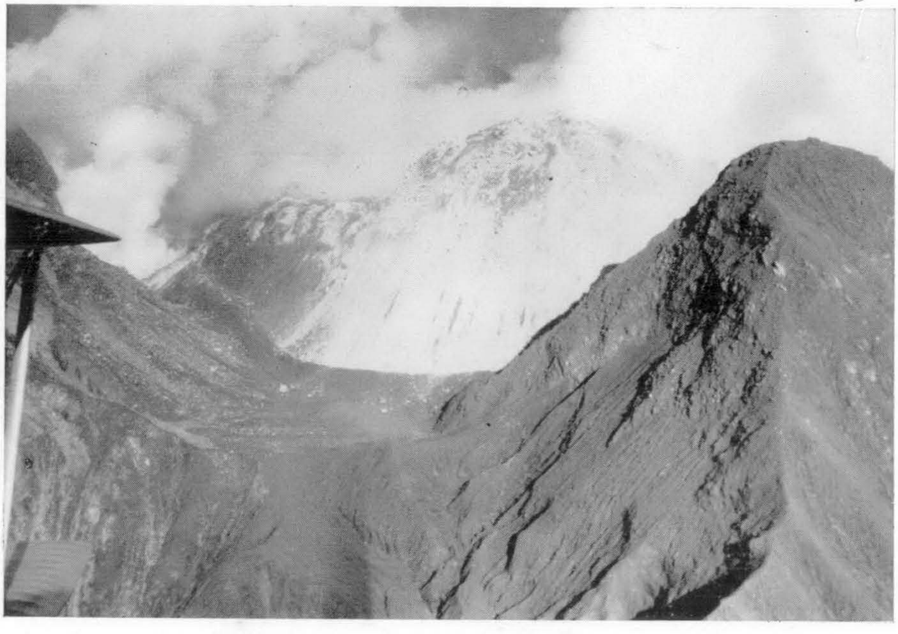


Fig. 127. 28.3.51. Uplift and lateral extension of the south-eastern sector has attained its limit.

Fig. 128. 20.3.51. Limited dome development on western side of crater.

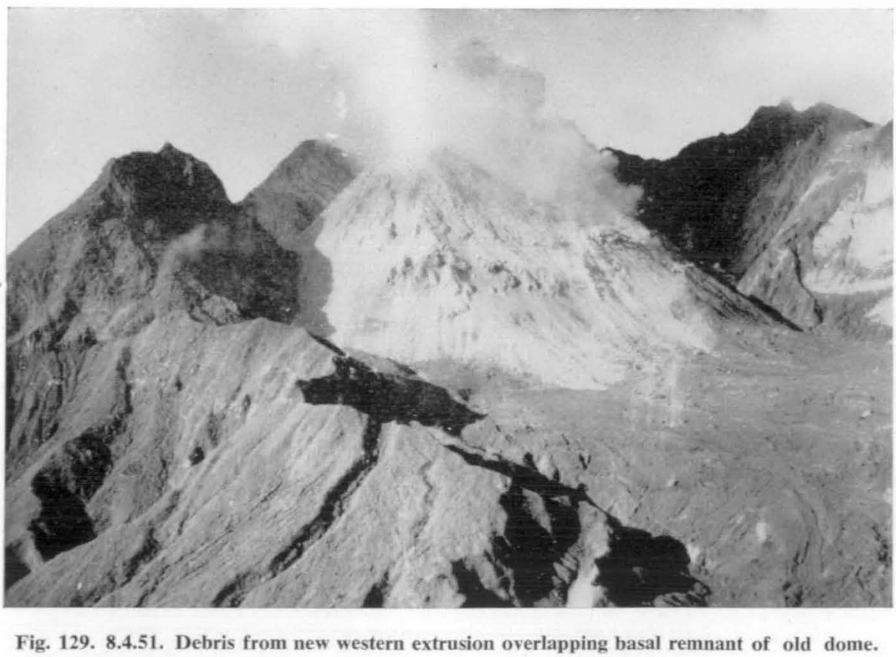


Fig. 129. 8.4.51. Debris from new western extrusion overlapping basal remnant of old dome.

Fig. 130. 1.5.51. The 'twin domes'.

Fig. 131. 21.6.51. The hog-backed spine is visible as a peak on the hot western (right) side of the dome.

Fig. 132. 21.6.51. The western spine stands about 300 ft. above the surface of the dome.

Fig. 133. 9.7.51. The huge rounded block of the structure begins to fracture.

Fig. 134. 21.6.51. The north-western aspect of the hog-backed spine (photograph tilted).

Fig. 135. Late July, 51. Advance of northern sector of dome.

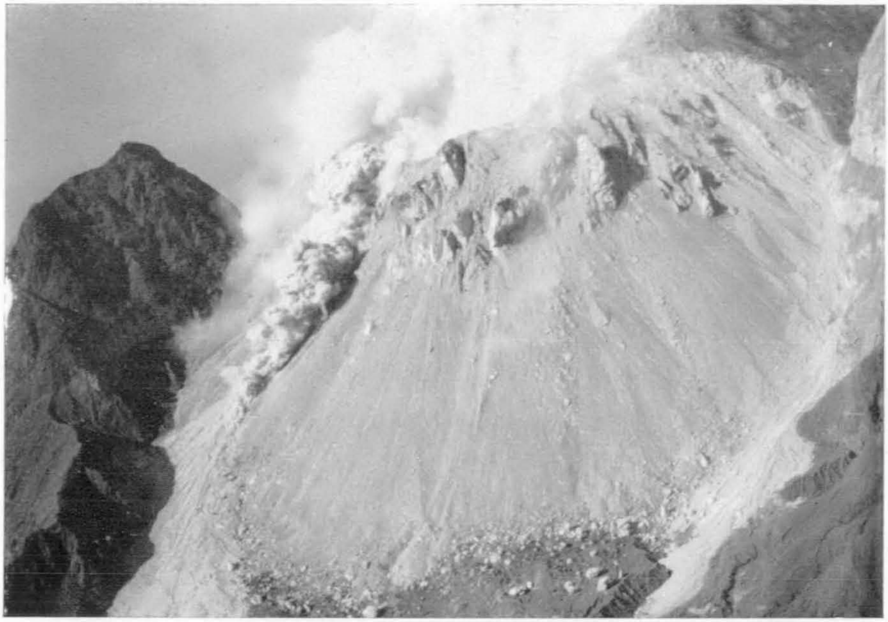


Fig. 136. August, 51. Avalanche descending flank of new northern extrusion (photograph tilted).

Fig. 137. The knife-edged spine emerging from the centre of the dome.

Fig. 138. 15.8.51. Movement of the northern sector draws to an end.

Fig. 139. 10.10.51. Heavy avalanches from uplift of eastern dome sector.

Fig. 140. February, 52. Dome with terminal spine.

Fig. 141. February, 52. Close view of spine from the south.

Fig 142. June, 55. North-western aspect of dome.

Fig. 143. 7.3.51. Horizontal banding in remnant of first dome.

Fig. 144. August, 51. Platy cleavage and brecciated texture of lava on northern flank of dome.

Fig. 145. A breadcrust bomb on the western slopes.

The spine, a tapered, knife-edged keel of rock, was aligned roughly north-east and at its maximum stood at least 400 feet above the dome surface.

This monolith showed neither the plastic deformation nor the slickensides of the western spine; it seemed merely a rough slab with some differences in the texture of the constituent lava. A narrow zone of red lava which appeared similar to the farinaceous material found in cavities and fracture zones was on the nearly vertical north-eastern end of the "keel". The remainder of the spine was composed of a grey lava which showed a banding orientated roughly at 45° to the vertical.

Uplift of the central spine ceased about mid-August and at the same time the northern flank showed signs of cooling (fig. 138). About mid-October extrusive activity was resumed with a rise in the eastern sector of the dome, and heavy avalanches of debris descended the north-western flanks (fig. 139). The focus of extrusion moved back to the centre of the dome early in November and after that time little movement occurred elsewhere, just as, at Pelée in 1902, the movement ultimately became confined to the central area of the dome (Lacroix, 1904, p. 136).

The central growth took the form of a series of slowly extruded terminal spines which rose from various parts of the summit area. These structures lacked the clearly defined form of earlier spines and they often appeared as groups of massive rectangular blocks rising from a mound of debris. This appearance may have been given by an extrusion rate which kept just ahead of the disintegration. However, during the comparatively rapid movement in early 1952, a spine on the western side of the summit produced a round-backed form which was almost a mirror image of the hog-backed spine of June 1951 (fig. 141). Although its western flank was rubble-covered rather than smooth, it had the essential rounded form and steep inner face of the half-horn spine. This was the last occasion on which a form of this kind was observed. The subsequent terminal extrusions all crumbled away eventually, leaving the final structure with a gently rounded summit (fig. 142).

Internal Structure.

Little in the way of internal structure is to be expected in a dome which grows in a piecemeal fashion by localized extrusions. It is perhaps significant that the core remnant left from the first dome, which had been extruded in a more or less homogeneous fashion, should show evidence to suggest concentric banding (fig. 143). Observations of later localized extrusions indicated no regularity of internal structure. The small terminal spines which rose from the eastern sector of the dome in March exhibited a vertical banding orientated roughly north-south. In the western hog-backed spine, on the other hand, the banding was parallel with the smooth rounded face. The spines which rose from the southern sector of the crater appeared to be invariably massive. The central part of the northern sector also was composed of a massive lava which developed a platy cleavage parallel to the talus slope (fig. 144). The material on the flanks of this structure seemed to be composed of a breccia which crumbled readily. Brecciated lava was not an uncommon feature of the dome during the early stages of its growth; the most notable occurrence was observed in the rising flank of the western sector in April 1951. The base of this structure was composed of a fine-grained unconsolidated breccia which was overlain by massive lava. Unfortunately, by the time this side of the dome could be approached the breccias had been concealed by debris from later extrusions.

Breccias were not common among the debris on the flanks of the dome during the later period of extrusion; but a friction breccia was collected from the summit in January 1953, and is described below.

THE LAVAS.

Lithology.

The lavas of Lamington are typically sub-compact granular andesite containing phenocrysts of plagioclase, hornblende, and biotite. They are mostly massive, but a rough banding and a platy cleavage, apparently due to the drawing out of the more glassy elements of the groundmass, are fairly common. The colour of the lavas ranges through shades of grey and red-brown; the most common colour of the unweathered rock is a light and medium grey. The large white phenocrysts of plagioclase are conspicuous in the darker groundmass.

Texture.

The texture of the lavas ranges from a pumice to an apparently non-vesicular coarse-grained rock. Pumiceous material, which is relatively uncommon, is found as light-coloured pea-sized fragments and angular blocks up to a foot across. Many of the blocks appear to have a granular rather than vesicular texture—a mass of crystals welded together by fibrous webs of glass. The cavities are bounded by rough hackly surfaces, and across them stretch numerous connecting filaments of glass. At the other end of the textural scale is a slowly cooled coarse-grained andesite containing crystals up to 4-mm. wide of biotite, plagioclase, pyrite, and quartz. Cavities appear to be entirely absent from these rather uncommon specimens.

Most of the Lamington lavas have an intermediate texture which is generally granular or sugary; they have the appearance of a mealy aggregate of separate crystals bound together by an irregular aphanitic groundmass. The lava is described above as sub-compact, the term being used in the sense of non-vesicular: it has no true vesicles, but on close examination is invariably found to contain small hackly-surfaced cavities which give it an inherent porosity.

Porosity.

That nuées ardentes are composed of gas-emitting fragments is now generally agreed, and the lavas capable of producing nuées must therefore be porous. Macgregor (1937, p. 32) found porosity to be an important textural feature of the lavas of Pelée and Montserrat, and emphasized its role in the mechanism of the nuée.

Rough measurements of the effective porosity of Lamington lavas were made. The rocks were saturated by placing them in water and reducing the air pressure to about 7 inches of mercury. The water absorbed by the sample was then measured, and the bulk volume of the saturated sample determined by displacement. The results are shown in Table I. The methods used were very crude: both the use of water to fill the pore space and the incomplete vacuum would tend to give an underestimate of the effective pore space. Thus the figures obtained are minimum values, and at best they give a relative idea of the effective porosity.

TABLE I.

Lava Sample.	Bulk Volume. cc.	Pore Volume. cc.	Effective Porosity. %
Old lavas—			
Eastern crater wall	208	25	12
Southern crater wall	122	15	12
Western crater wall	138	31	22
New lavas—			
Nuée-deposited (pumiceous): March, 1951 ..	202	80	40
North slope of dome: July, 1951	124	18	14
February, 1952	116	8	7
East slope of dome: January, 1953	144	20	14
South slope of dome: January, 1953	81	6	7
West summit of dome: January, 1953	78	9	12
Terminal spine: January, 1953	71	10	14
Vulcanian lava—			
Tavurvur volcano, Rabaul, 1941 eruption ..	90	4	4

The porosities of the old and new lavas are closely comparable. The relatively high value for the western wall is probably due to more advanced weathering: the groundmass of this lava is less glassy and more altered than that of other lavas; some samples are almost friable.

The results do not reveal conclusive evidence of a decline in effective porosity of the dome rocks with passage of time. Such a relationship is suggested by the samples collected from the north slopes in 1951 and 1952, but the other results suggest that there is more variation in individual parts of the dome than in the successive lavas. Field examination of the material in the talus apron of the dome during 1951 and 1952 gave a general impression that the lava extruded from the eastern sector of the dome was more porous than the others. There were, however, local exceptions.

The pumiceous sample collected from the deposit left by the nuée of 5th March, 1951, was found in a bed of similar blocks, up to a foot across, on the north-western slopes of the volcano about 4 miles from the crater. Although these blocks cannot be taken as typical of the nuée material—the greater part of the fragmental material was neither pumiceous nor very obviously porous—their presence does suggest that certain parts of this large nuée consisted of blocks containing glass so highly charged with volatiles that a powerful intumescence during the descent of the nuée had dilated them into a pumiceous form. The specific gravity of these blocks is slightly greater than that of water; so they are, by this criterion, not true pumice. Lighter pumices are rarer; they consist of pale angular fragments which are minutely vesicular, and were produced in small quantities by the climactic explosions of January 1951, and some later explosions.

The specific gravities of the other samples tested for porosity range from 2.0 to 2.5.

Breadcrust Bombs.

The aphanitic texture noted as characteristic of the Lamington lavas persists even in the rather uncommon breadcrust bombs discovered on the slopes of the mountain. These angular blocks have a quite well-developed surface-fracture pattern, and shrinkage along the fractures is evident, but there is no suggestion of a dense vitreous crust (fig. 145). One specimen seemed slightly more porous than the dome rocks, but the texture did not apparently change from the centre to the surface. The angular form of the bomb suggests that it partly solidified at the moment of ejection. The rock apparently contained sufficient residual molten glass to cause shrinkage during the sudden chilling of aerial flight, but insufficient to produce a vitreous crust and a marked internal vesiculation. Many of the blocks of a nuée ardente were undoubtedly in a similar semi-consolidated condition. In these circumstances the annealing affect of the hot cloud prevented breadcrust structure from developing.

The annealing effect of the nuée heat on the residual glass of the lava was clearly illustrated, for slightly lower temperatures, by the behaviour of blocks brought down by the incandescent ash-flows. Blocks which were stranded on the cold surfaces of valley walls and ledges fractured during the relatively rapid cooling process and usually disintegrated into fragments, but even large blocks deposited on the hot ash beds remained intact.

The curious plastic-solid condition of the lava, which seems responsible for these bombs, was further revealed in a fragment collected in the trough to the south of the dome. This fragment was quite massive and undifferentiated in texture, and yet one side contained wide contraction cracks about ¾ inch deep. It may have been a fragment from a spine. Day and Allen (1925) report breadcrust surfaces on the dome rocks of Lassen Peak, and Lacroix (1904) describes a semi-consolidated type of breadcrust bomb from Pelée.

Inclusions.

Inclusions of various kinds are abundant in lavas of the recent eruption, and mostly occur as sub-angular masses with clear-cut boundaries. Many consist of coarse dunite, hornblendite, and the more basic variants of the volcanic magma. A contact aureole of biotite and hornblende is a common feature of blocks of medium-grey dunite which measured up to 8 inches across. The dark blocks of coarsely crystalline mafic material are perhaps the most conspicuous inclusions. They were originally thought to be formed by segregations of the hornblende in the lava, for in many inclusions of an intermediate texture the hornblende appeared to be more abundant than in the encompassing lava. Microscopic examination, however, has revealed the dark blocks to be holocrystalline hornblendite containing primary anhydrite, and the finer-grained inclusions to be cognate lavas. Because periodotites and dunites occur in the Goya Range south of Lamington, and dunites in the small hills near Divinikoiari village north-west of Lamington, it is not remarkable to find ultra-basic xenoliths brought up from part of the basement of the volcano.

Williams (1932) points out that an abundance of basic inclusions is so common in domes that it is almost characteristic of massive volcanic protrusions. He was referring principally to autolithic enclosures—more basic variants of the lava itself—which were a feature of Pelée. The inclusion of rocks of obviously plutonic origin seems to be rather uncommon.

PETROLOGY.

Samples for micropetrological examination were collected during the active period of 1951 and 1952. During the first five months of activity, only ejecta in the nuée deposits and on the immediate western slopes of the mountain were collected, except during an ascent into the crater by Dr. N. H. Fisher, Mr. Crellin, Leslie Topue, and myself, by way of the avalanche valley on 11th February 1951. Samples were collected from the dome, the nuée deposits in the valley, the old flow on the western side of the valley, and the incidental ejecta found farther from the crater. During the eighteen months from July 1951, numerous visits were made to the crater to check conditions of activity and to collect representative lava samples from various parts of the growing dome. Air inspections had revealed a considerable variation in the texture of the rocks in different sectors of the dome, and it was suspected that some progressive change in mineralogical composition might have taken place during the long period of extrusion.

Avalanches from the dome had become so infrequent by January 1953 that it was practicable to explore the summit area. Samples were collected from the terminal spines, and on the western summit area interesting remnants were found of an earlier spine surface which showed evidence of the stresses involved in an extrusion of this kind. This was the first time that such stressed rocks had been found on the dome. During the earlier phases of dome activity frequent avalanches on the western side had made the collection of samples from the slopes in this sector too dangerous.

The combination of avalanches on the western side and active vents in the narrow southern trough resulted in the unfortunate omission of rocks from the southern sector of the western wall from the collection of samples of the old lavas of the crater walls.

Specimens collected during the early phases of the volcano's activity were briefly described by W. B. Dallwitz (unpublished). Subsequent material representing the old and new lavas was examined by J. Kerry Lovering, and her report is included as Appendix II. (p. 110). I have examined Mr. S. J. Paterson's thin sections of the lavas from the Hydrographer Range and the thin sections from the Lamington lavas which appeared to be of special interest.

Microscopic examination indicates that the vulcanism of the region is dependent on an andesite magma rich in volatiles, for, typically, the lavas contain an abundance of hornblende and biotite. Hypersthene andesites in the material so far collected are of minor importance.

The rocks have petrological affinities with those of other volcanic areas which have produced Pelēan type eruptions and lava domes. The chemical analyses (Table III.) reveal similarities with the lavas of the Lesser Antilles, the Crater Lake area of Oregon, and especially with certain domes of submarine origin (Bogoslof, Sangi Is.). Many of Macgregor's findings on the rocks of the Lesser Antilles are paralleled at Lamington. Resorption of the hornblendes and biotites is a conspicuous feature.

EARLY LAVAS.

The Hydrographers.

The Hydrographer Range, lying adjacent to Lamington on the south-east side, is a deeply dissected volcanic complex which represents an earlier phase of vulcanism in the area. Examination of specimens collected by S. J. Paterson near Oro Bay and from the Borfu and Gorpei Rivers on the northern slopes of the range suggests a common magma for the two centres. The lavas appear to be andesites, porphyritic in plagioclase, hornblende, biotite, and hypersthene, of a type very similar to those of Lamington. The phenocrysts are generally smaller, and in one specimen are oriented along flow-lines. Although the lavas have the rough surface of a porous rock, on the whole they seem more compact, and lack the more obvious porosity of the lavas of the active volcano. One dark-grey specimen contains abundant phenocrysts of pyroxene and olivine, and its sub-vitreous surface texture and dark colour appear more typical of a basalt.

The hornblende crystals are partly or wholly replaced by magnetite, pyroxene, and plagioclase. Both dark brown and bright red types of amphibole are present, and their extinction angles are very close to 0°. The red hornblende is only marginally altered to magnetite, whereas the brown is commonly completely replaced by opaque black masses. The biotites have similarly reacted to the oxidation processes which have taken place in the lava.

The plagioclase phenocrysts are zoned, and completely twinned, and contain spongy masses of minute inclusions of glass which form internal zones or broad margins round the crystals. Phenocrysts of pyroxene, olivine, and magnetite are present in most lavas.

The Lavas of Lamington Cone.

The only specimens of older lavas examined are from the crater walls, a flow on the north-western side of the cone, the columnar flow which is a conspicuous feature of the western wall of the avalanche valley, and a dyke intruding the old agglomerate in the upper channel of the Ambogo River (figs. 2 and 141a). The remaining walls of Lamington crater consist mainly of massive rocks, with the exception of the northern end of the west wall, where three conspicuous flows appear (see fig. 124). The

MOUNT LAMINGTON VOLCANIC AREA

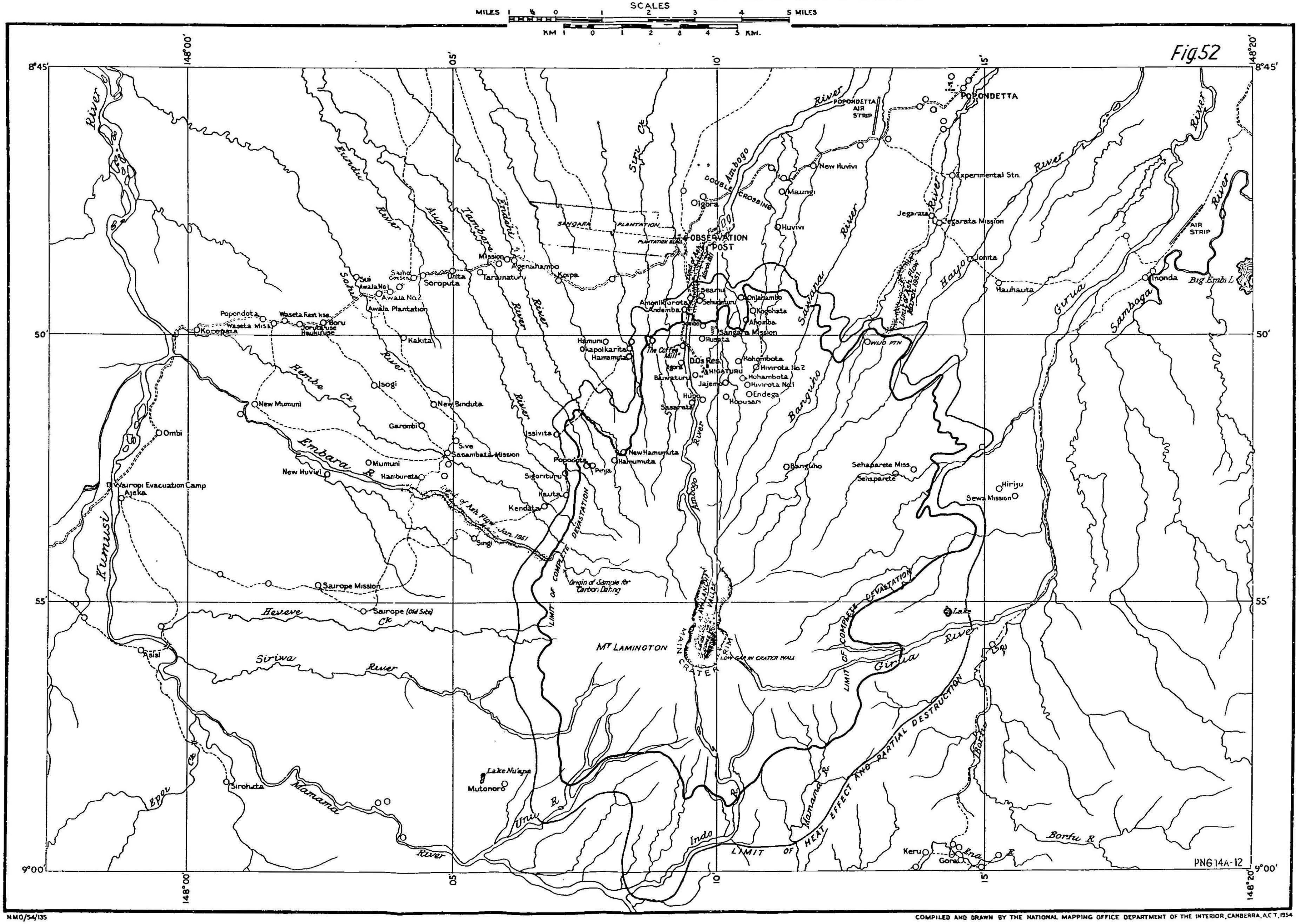


Fig 52

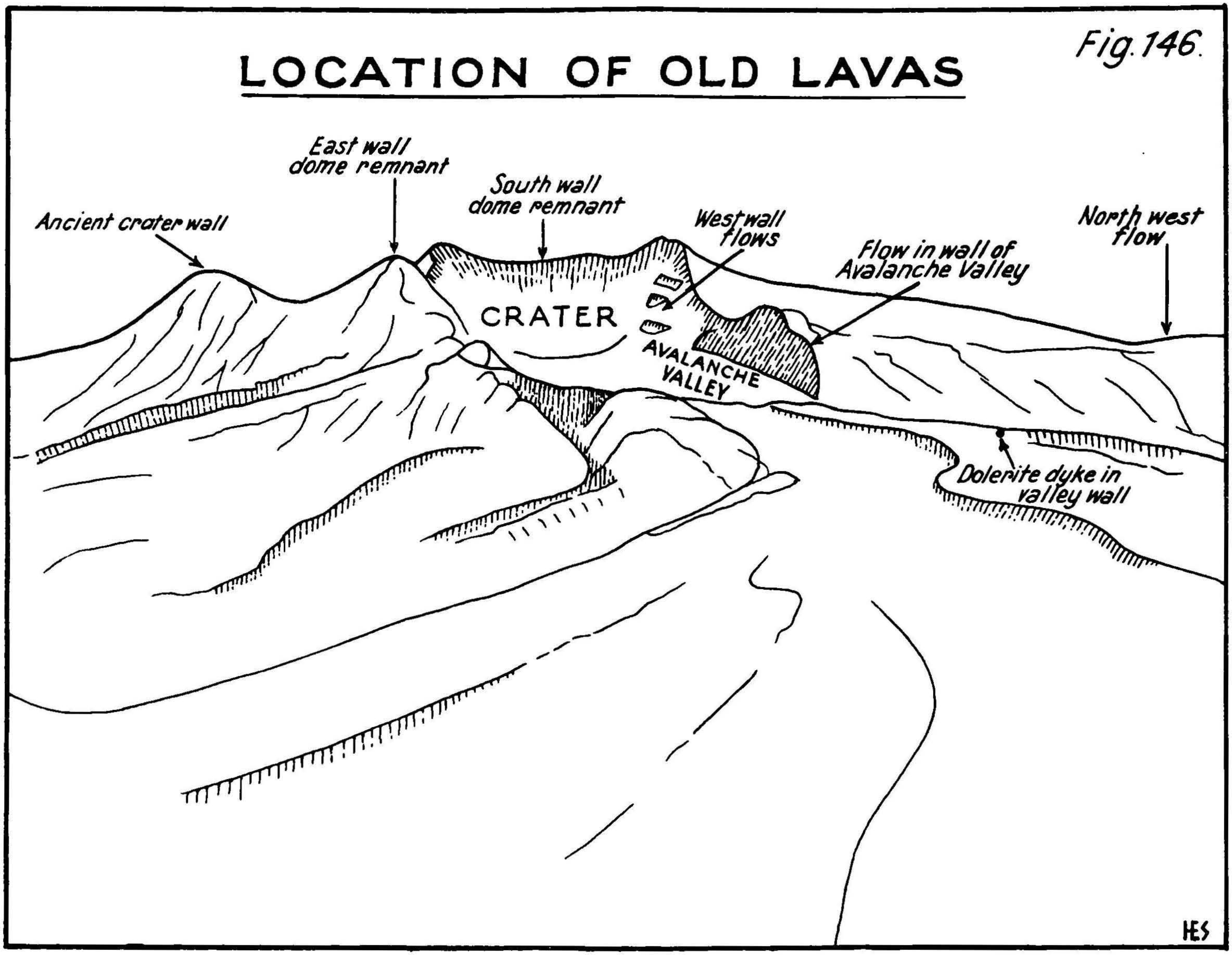


Fig. 146.
LOCATION OF OLD LAVAS
East wall dome remnant
South wall dome remnant
Ancient crater wall
West wall flows
North west flow
Flow in wall of Avalanche Valley
CRATER
AVALANCHE VALLEY
Dolerite dyke in valley wall
HES

northern end of the eastern wall may be formed by a short viscous columnar flow. The general massiveness of the crater walls suggest that they consist chiefly of the remnants of three earlier domes, situated on the east, south, and south-western sectors of the crater. In effect the present crater is a vent developed at the foot of these three structures, which represent former crater vent positions.

Flow Lavas.—The flow lavas of the western wall are described in detail in Appendix II. They are light-grey porphyritic andesite, and appear to be more weathered than the dome rocks, probably because they cooled more slowly from a higher temperature, and formed a less glassy groundmass. So numerous are the microlites that most specimens appear holocrystalline.

The columnar flow in the western wall of the avalanche valley consists of a men, and specimens of the new and the old lavas cannot be told apart. They are all olivine, and magnetite. It differs from the lava of the western wall in the slightly finer grain of its almost holocrystalline groundmass and the relative abundance and size of its hornblende and biotite phenocrysts: phenocrysts are fewer and smaller than in the western wall lavas, and are more altered. Almost all the hornblende and biotite is pseudomorphed by magnetite, pyroxene, plagioclase, and chlorites. The pyroxene occurs as small single grains and clusters.

Dome Lavas.—The dome rocks appear very similar to one another in hand specimen, and specimens of the new and the old lavas cannot be told apart. They are all porphyritic andesites with about equal parts of phenocrysts and groundmass. Microscopically they are most easily differentiated by the type and degree of alteration of the hornblende and biotite.

The *south wall* rises to an extremely steep-sided peak, more than 1,000 feet above the floor of the southern trough. It is essentially massive and is composed of a green-hornblende andesite, some of which is hydrothermally altered. This alteration is not surprising because the most active gas vents of the recent eruption were at the base of this wall, and during later stages of activity, when the southern trough became choked with mud and rock, gas vents broke out high up the wall both inside and outside the crater. Obviously quite a large section of the wall structure was exposed to the volcanic gases. Similar processes probably operated in the past.

The *east wall* appears to be an old dome remnant bounded on the east by a composite wall. The centre and southern part of the crater wall are massive, but at the northern end, next to the avalanche valley, a great jointed arch-shaped rock structure is revealed. This structure was originally thought to be a shell or carapace, but the similarity of its chemical composition to that of the western wall (Table III., Nos. 2 and 4) and its relatively low proportion of phenocrysts suggest that it is a short viscous flow originating from the adjacent dome.

The rocks from both these structures are magnetite-lamprobolite andesites containing phenocrysts from 0.1 to 4 mm. in size. The phenocrysts are less abundant in the shell or flow rock than in the main rock of the wall (40 per cent. as against 55 per cent.). One of the most conspicuous features of the lavas of the east wall is the extensive alteration of the hornblende and biotite. The hornblende is altered to magnetite, pigeonite, and plagioclase, and the biotite is largely replaced by magnetite.

THE LAVAS OF THE RECENT ERUPTION.

The lavas of the recent eruption are porphyritic andesites, very similar in chemical and mineral composition to the rocks of the crater walls, but differing from the old lavas mainly in the relative abundance of unaltered hornblende. Among the dome lavas, andesites containing oxidized hornblende, or lamprobolite, are common; those with green hornblende occur less commonly and only in a few specimens does hornblende exhibit magnetitic resorption. The fragmental lava from the explosive activity ranges in composition from a pumiceous green-hornblende-bearing andesite to andesites containing the much-altered amphiboles characteristic of the old cone lavas.

Fragmental Material.

The predominance of the green-hornblende-bearing andesite in all ejectamenta except the ash of the nuée deposits suggests that this is the most active of the lava types in the eruptive mechanism.

Small pumice blocks were ejected over a wide area by the climactic explosions. Specimens collected west of the crater beyond the limit of the area devastated by the glowing cloud are finely vesicular, contain numerous phenocrysts, and are comparatively dense. They are all andesite, porphyritic in plagioclase, green hornblende, biotite, magnetite, apatite, and anhydrite. The groundmass may be clouded and porous or clear and colourless with numerous microscopic vesicles, many of which are flattened and drawn out into wavy lines. The groundmass in some specimens appears clouded with minute crystal fragments as if the melt had taken up dust during the process of ejection.

Ash which fell farther to the west on Yodda and Port Moresby is composed largely of the same pumiceous green-hornblende andesite, finely sub-divided. The ash that fell on Port Moresby is derived, almost entirely, from the highly gas-charged magma which formed the pumices. It contains abundant crystal fragments, among which green hornblende is the predominant ferromagnesian mineral. The numerous clear glassy fragments contain the microscopic vesicles that are a common feature of the pumices.

The ash from the nuée deposits, on the other hand, is almost free of such minutely vesicular fragments. The glassy fragments are compact, typically crowded with microlites, and sometimes devitrified. Correspondingly, the hornblende is mostly oxidized, and many crystals, like those of the old dome lavas, are greatly altered. These observations apply to ash collected from the valley deposits left by the eruptions of 24th February and 5th March, and also to the coarse ash forming the base of the deposit that fell on Higaturu on 21st January. The upper layer of the Higaturu deposit consisted of fine ash which fell largely from the expansion-cloud formed by the nuée. Green hornblende was more abundant in this upper layer and also in similar material that fell from the nuée of 5th March (fig. 44).

The large fragments in the nuée deposits varied more widely in composition than the fine constituents. Most of the rocks collected from the deposits of the eruption on 21st January consisted of hornblende andesites which resembled very closely the old lavas of the crater walls. The green-hornblende andesite of the south wall, the pyroxene andesite of the west wall, and the magnetite-lamprobolite andesite of the east wall are all represented in this material. Blocks from the ash flows of February and March, on the other hand, are all of new lava and contain unaltered hornblende. One specimen from the March eruption contains phenocrysts of plagioclase, brown hornblende, biotite, pyroxene, olivine, magnetite, apatite, and anhydrite. All other specimens from these deposits contain green hornblende; pyroxene and olivine may or may not be present. The groundmass may be almost entirely glass or partly microcrystalline. Examination of a section from a breadcrust bomb reveals a green-hornblende andesite whose characteristics are the same as those of the blocks collected from the later nuée deposits.

Extrusion-Breccias and Stressed Rocks.

Extrusion breccias and stressed rocks are the mechanical variants of the normal lavas of the dome. The large western spine extruded in mid-1951 had an extensive smooth, curved eastern face, which emerged at a relatively low angle from the dome. This face was slickensided, and was found to be composed of brecciated and distorted rocks of three types—

(i) A compacted friction-breccia composed of fine mineral fragments in a matrix of red iron oxides;

(ii) A hard dark-red lava containing a layer in which fractured feldspars produced well-defined lineation;

(iii) A pinkish-grey lava distorted into an elongated parallel-sided block with a foliate, almost gneissic, banding parallel to its shorter sides.

Type (i) is earthy to finely granular and has a relatively smooth contact surface with small parallel striation grooves, and is coloured with patches of darker red mineral powder. The thin section reveals a layer 2 to 3 inches deep, of fine-grained rock-fragments remarkably uniform in size. The hornblende fragments are of the brown variety and commonly twinned.

Type (ii), the dark-red lava, contains a bright-red pleochroic lamprobolite, zoned around darker centres, and commonly twinned. The extinction angle ranges from 0° to 10°. Red biotite phenocrysts are generally twisted into strained positions, showing bent cleavage planes. Many pyroxene and olivine phenocrysts have coronas of lamprobolite. Elongated zones of shattered feldspars extend across the section. The glassy groundmass contains shattered crystal fragments oriented linearly.

A section of the gneissic specimen, type (iii), shows the foliation to be due to shatter-zones of feldspar and brown hornblende. The hornblende is largely altered to magnetite, and many crystals are zoned round a darker centre. The pleochroism is so intense in some crystals that the mineral is almost opaque in the dark-brown position. Phenocrysts of magnetite are numerous, but little olivine, pyroxene, or biotite is present. The glassy groundmass contains numerous crystal fragments.

The texture and distortion of the rocks in this frictional zone suggests that the lava was extruded in a plastic condition close to the point of solidification. The bulk of the spine mass yielded to plastic flow. Marginal parts which solidified were ground into a fine-grained breccia; almost solid layers fractured under stress and were compressed into foliated gneissic blocks. The more fluid parts yielded viscously, shattering the contained phenocrysts and strewing them in linear " pipes " throughout a zone about 1 inch deep.

TABLE II.—CHARACTERISTICS OF LAMINGTON LAVAS.

	Old Lavas.					New Lavas.		
Locality	South Wall.	West Wall.	East Wall. (core)	East Wall. (shell)	N.W. Flow.	Type I.	Type II.	Type III.
Rock Name	Hornblende andesite	Pyroxene andesite.	Magnetite-lamprobolite andesite	Magnetite-lamprobolite andesite	Hypersthene basaltic andesite	Lamprobolite andesite	Olivine-pyroxene-anhydrite-lamprobolite andesite	Anhydrite-hornblende andesite
Groundmass	45% Devitrified	70% Microcrystalline interstitial glass	45% Microcrystalline interstitial glass	60% Microlites in glass	50% Microlites in glass	50% Glass ..	53% Microcrystalline interstitial glass	53% Glass
Phenocrysts—								
Feldspar: Core	..	An56	An80	Bytownite	An84	An51–48	An65	An65–60
Zones	An48–38	An45–38	An42–32	An42–37	An67–84	An65, An35–26	An65, An45–30	An65, An50–35
Per cent.	33%	5%	37%	25%	41%	23%	28%	26%
Amphibole: Green hornblende ..	11%	..	..	..	..	..	..	13%
Lamprobolite ..	..	3% (15%)	8%	3%	..	19%	9%	..
Biotite: Green..	3%	..	..	..	..	..	..	4%
Brown	..	2%	2%	1%	..	..	1%	..
Red	..	..	..	..	..	2%	..	..
Pyroxene	2%	7%	X	2%	pig. 5% diopside 3% }	1%	3%	1%
Magnetite	5%	12%	8%	6%	1%	2%	2%	2%
Anhydrite	X	..	..	..	..	1%.	1%	1%
Apatite	X	..	X	X	..	1%	1%	..
Pyrite	X	..	..	..	..	..	..	..
Hematite	..	X	X	..	..	..	..	..
Olivine	..	..	X	2%	..	1%	1%	X

Dome Lavas.

The first lava collected from the dome, on 11th February 1951, was a porphyritic lamprobolite andesite, which closely resembled the lava of the eastern crater wall; this suggests that the whole structure at that stage of its development was covered with a fragmental mantle of old conduit material. The later lavas—new lavas—are porphyritic andesites in which amphiboles and biotite are rarely resorbed. Three types have been identified (their characteristics are shown in Table II.)—

Type I: anhydrite-bearing red-lamprobolite andesite;

Type II: anhydrite-bearing brown-lamprobolite andesite;

Type III: anhydrite-hornblende andesite.

Most of the dome is composed of Type II. lava. Type I. can be found anywhere, but is much less abundant; its distribution may be related to vents and fracture-zones in the dome. Type III. seems to have been extruded only from the northern sector of the dome, for all speciments were collected from the northern talus apron.

Inclusions in the lavas consist of autoliths, hornblendite, and forsterite veined by enstatite, and are described in Appendix II.

CONSTITUENTS.

Phenocrysts.

Plagioclase.

In both the old and new lavas, plagioclase is normally the most abundant mineral among the phenocrysts. The lava from the dome contains on an average about 30 per cent. porphyritic feldspar. The flow-lavas vary much more in their feldspar content, ranging from 41 per cent. in the north-western flow to 5 per cent. in the thin flow near the base of the western wall. The composition of the zoned feldspars ranges from labradorite-bytownite to oligoclase-andesine; the new lavas are slightly more acid than the old. Type II., the most common lava of the recent eruption, has feldspar with andesine zones slightly less calcic than the more acid of the old lavas; and Type I. has oligoclase-andesine zones about cores less calcic than those of any other lavas. The presence of Type I. lava in fracture-zones of the domes suggests that it was the last of the dome rocks to solidify.

Characteristics common to feldspar phenocrysts in all lavas include oscillatory zoning and complex albite, carlsbad, and carlsbad-albite twinning. Many of the crystals are fractured, and, in the pumices, disrupted. Lacroix attributed this effect in some of the lavas of Pelée to swelling of the vesicles. Many crystals show resorption phenomena. Most have inclusions, which may occur in zones, and which commonly consist of fine-grained glassy or anisotropic material. Spongy inclusion zones appear to be more common in the flow lavas than in the dome lavas.

Hornblende.

In the dome rocks, whether new or old, hornblende is by far the most abundant ferromagnesian mineral; but in the old flow rocks, it is almost completely resorbed or is absent (see Table II.).

The instability of hornblende under volcanic conditions is manifested in the variety of types present and the degree of alteration. Washington (1896) expressed the view that many pyroxene andesites may have derived their pyroxene from the disintegration of hornblende; confirmation of this view appears to be demonstrated by the distribution and degree of alteration of the hornblende of the Lamington lavas. The amphiboles of the recent eruption are almost invariably unaltered; whereas those of the old lavas show every stage of reconstitution from narrow magnetic rims to complete replacement.

The old flow lavas contain the most highly altered hornblende. Alteration is very advanced in the thin flow of the western wall; almost complete in the thicker flow of the western side of the avalanche valley; and hornblende has disappeared completely in the flow on the north-western slopes. Pyroxene is much more abundant than in the dome lavas and the groundmasses are hypocrystalline.

The quicker cooling of the dome lavas is shown by their protrusive form and less crystalline groundmass. The hornblendes are less altered; alteration is greatest in the east wall dome and least in the dome of the present eruption. The brown hornblendes of the east wall dome are partly resorbed at the rims, and in places in the centres, into magnetite, pyroxene, and plagioclase. The characteristics of the lava of its northern sector suggest that it was at or near the temperature of flow movement. The green hornblende of the southern wall dome is deuterically altered to green actinolite, biotite, and colourless chlorite, with rims of fine-grained magnetite and pyroxene.

Lavas of the new dome and the old east wall dome both have groundmasses of similar texture, which suggests that the cooling rates were approximately the same. The characteristic lack of alteration, therefore, in the amphibole of the new dome lavas, contrasted with the advanced alteration of the east dome lavas, could be taken to indicate that the new dome was extruded at a lower temperature.

Green hornblende can be converted into the red-brown varieties by heating in oxidizing or neutral atmospheres. The process is apparently an oxidation or auto-oxidation effect in which the ferrous iron is converted into ferric iron with loss of hydrogen (Macgregor, 1936). The change is accompanied by a decrease in the extinction angle which begins at 750°, approaches zero at 800°, and becomes zero at 900°. At temperatures around 1100° the mineral disintegrates into magnetite and other products, a process we have seen to be common among the old lavas. This property of hornblende suggests that amphibole varieties present in the lavas of the recent eruption may have originated from a common green or brown hornblende which has been subjected to different pressures, rate of cooling and possibly temperature maxima and concentration of volatiles, during the process of eruption. The distribution of the type of amphibole correlates broadly with the degree of glassiness of the groundmass. This relationship at first sight appears to support conclusions drawn from observations at other volcanic centres where cooling rates appear to be the determining factor (Brouwer, 1920; Macgregor, 1936). Some evidence can be found to suggest that distinctive surface thermal conditions were associated with difference in the amphibole at Lamington, but an awkward individuality in the total constitution of the lava types casts doubt on the significance of this relationship. First let us examine the proposal with its field relations.

Green Hornblende is present in all the pumices and the more glassy rocks of the nuées ardentes. It is quite abundant, as we have seen, in the dusts of the climactic explosions, and perhaps the most interesting facet of its distribution is its appearance in the lavas extruded from the northern sector of the dome. The cooling rate of the dome lava with its gradual movement and attendant hot gases is very slow, compared with that of the ejecta. It would normally be expected that under such conditions the red-brown amphiboles would form—which is true of the great bulk of the dome; but in the northern sector green-hornblende lava was formed. The groundmass of the green-hornblende lava is slightly more glassy than that of lavas from other sectors of the dome, which may suggest that cooling rate rather than temperature is responsible for the presence of green hornblende. The cooling rate of the northern sector may be related to the configuration of the crater. The absence of a wall on the northern side of the crater seemed to have two effects which could contribute to a more rapid cooling: it allowed the talus apron to slip down the sloping avalanche valley, so that the insulating blanket of superficial rocks was removed from the upper part of the dome and the core was exposed to direct atmospheric cooling; also, if the dome lava were to flow plastically, it would be most likely to do so to the north. That in fact it did flow is suggested by the northward advance of the dome in July 1951, which removed the northern se ctor from exposure to the hot gas exhalation of the main conduit. The varying zones of origin of observed crater exhalations indicated less abundant gas from the northern sector.

These special cooling conditions, however, do not explain the distinctive mineral assemblage of this Type III. lava. It seems more likely that both the character of the amphibole and the other minerals are linked with conditions at depth. This question will be discussed further when considering the mechanism of the eruption.

Red-brown lamprobrolite is by far the most common amphibole of the new dome lavas. Its colour ranges from almost brown to a distinctive bright red-brown which is confined to the Type I. lavas. At some volcano centres the red-brown amphibole has been confined to rocks which are reddish and show mineralogical evidence of external oxidation. Macgregor (1937, p. 52) was inclined to think that this association was of significance in its mode of formation. Larsen and others (1937) report however that in the San Juan region the red-brown amphibole was not confined to reddened lavas. At Lamington the average lamprobolite is not associated with rocks of specific colour. The extreme bright red-brown amphibole is found almost exclusively in the dark red-brown lavas. Unfortunately the only analysis of this Type I. lava is an exceptional specimen which was only slightly reddened; nevertheless it is much higher in ferric iron than the other lavas (see No. 9, Table III.). The distribution of Type I. is significant: all specimens of the dark red-brown lava actually found in situ were collected from cavities near vents or fracture zones in the dome, the normal points for concentration and release of volatiles.

As a cavity lining the lava had a rough hackly surface and porous, almost farinaceous, texture characterized by irregular vesicles much larger than those in the containing rock. It appeared to be the equivalent in this granular andesite of a coarsely vesicular scoria in a basic lava. The form of the lava suggested that it had the consistency of dough, or paste, before solidification. A similar rough red-brown lava was found between adjacent blocks of the terminal spine, where in some places it seemed to form the matrix to large pebbles which had been rolled into well-rounded shapes by the grinding action of adjacent slabs. The slickensided surface of the great western spine also yielded specimens of red-brown lava which had been compressed and distorted into a compact rock.

The red farinaceous lava was seen again on the northern face of the knife-edged spine which rose from the centre of the dome after the summit activity of late June 1951. It seemed to represent the now elevated wall of the recently active terminal vent.

The implication of this distribution of the red-brown lavas is that volatiles play some part in the conversion of the contained amphibole from a brown or red-brown type to the highly oxidized bright red-brown variety. This change is effected by either special localized gas heating or by the oxidizing influence of gases. The specimen collected from the terminal spine is the only lava of the dome showing a clearly developed reconstitution of the amphibole to magnetite, pyroxene, and plagioclase. Such a change could be caused by localized superheating. It is noteworthy that the terminal spine zone was the only part of the dome that showed incandescent effects during the latter part of the eruption. The glow was unlike earlier manifestations in that it was confined for long periods to a small steady point source rather than a dispersed and changing incandescent zone characteristic of freshly extruded lava. It may be inferred that the spine extrusion had produced a fracture in the dome from which incandescent gas issued. Localized superheating, then, may have been a feature of the fracture zones in which the red-brown lava was characteristically found. Thus also with the Type I., containing the most oxidized amphibole, evidence is found of special superficial thermal conditions. And here once again the association is discounted not only by the distinctive nature of the other minerals but also by the characteristics of the amphibole itself. The fact that the cores of some crystals exhibit magnetitic reconstitution argues against superficial heating as the prime cause of formation of the bright red-brown lamprobrolite.

Biotite.

Porphyritic biotite is a constituent of all lavas except those of the north-western flow. The mineral is subjected to the same oxidation and resorption conditions as the amphiboles; for example, we find a green biotite in the Type III. lavas, a red-brown biotite in the Type II. lavas, and a red biotite associated with bright red amphibole in Type I. lavas. In the old lavas the biotite shows a similar instability; there are occasional rims of magnetite round the biotite crystals of the east wall rocks, and advanced magnetitic replacement in the east and west wall rocks. Biotite is corroded in some of the rocks from the nuée deposits, and clustered groups of hornblende and biotite are fairly common.

Pyroxenes.

Pyroxenes are most abundant in the hypersthene basaltic andesite of the north-western flow, in which hornblende and biotite are absent; the western wall flow-lava has also a high percentage of pyroxene, consisting of closely associated pigeonite and diopside. Among the dome lavas pyroxene occurs as anhedral grains. It is absent from the green-hornblende-anhydrite andesite, but is occasionally found in some of the green-hornblende-bearing pumiceous rocks. In the lavas of the recent eruption augite and pigeonite occur in small grains and clusters.

The greater abundance of pyroxenes in the older flow rocks, which are characterized by advanced resorption or absence of hornblende, gives some support to the view that some lavas derive their pyroxene from resorption of original hornblende.

Olivine.

Small percentages of olivine grains appear in most of the old and new lavas. The mineral is absent from the southern wall and north-western flow. In the old lavas it is generally cracked and in places serpentinized, and in the new lavas the fractured grains may be altered to pyroxene, serpentine, and hematite, and may have coronas of lamprobolite. Olivine is most abundant in Type I. andesite.

Magnetite.

Magnetite is most plentiful in the old lavas, where it forms pseudomorphs after amphibole and biotite; in the western wall it constitutes 12 per cent. of the rock, whereas in the recent lavas the amount is nowhere above 2 per cent. The mineral occurs more commonly as irregular grains than as euhedral crystals.

Anhydrite.

Anhydrite occurs as small irregular grains in the new lavas and the old lavas of the southern crater wall. It is an unusual component of volcanic rocks, and is possibly derived at depth from a hornblendite, which is commonly found as an inclusion in recent lavas. In the Komagatake lavas (Kozu, 1934) on the other hand, anhydrite was present in inclusions but not in the lava itself.

Groundmass.

The characteristics of the groundmass of the Lamington lavas reflect the type of activity that produced them, and certain features of this relationship are common to activity at other volcanic centres where Peléan eruptions have occurred. The various lavas of the 1902 eruption at Pelée were equally rich in phenocrysts, and Lacroix (1904, p. 153) divided them into four types on the basis of variation in groundmass. Type " a " was a vitreous andesite resembling obsidian, Type " b " a pumiceous type, Type " c " a porous andesite with many microlites of plagioclase, and Type " d " possessed an almost holocrystalline groundmass which was extremely rich in quartz crystals. Types " a " and " b " were characteristic of the explosive activity and types " c " and " d " were associated essentially with the slower cooling of dome extrusion. The nuée lavas consisted of Types " a " to " c " and the pumiceous Type " b " was much more abundant in the later nuées of the May-August and November-December explosive periods.

At Lamington crystallinity in the groundmass of the lavas is best developed in the old flow rocks, which contain little interstitial glass. The more viscous dome rocks have a cryptocrystalline groundmass with varying amounts of glass. Only the pumiceous rocks may contain abundant glass with few microlites; the lavas do not contain a representative of Lacroix' glassy Type " a ", and, at the other extreme, Type " d " is also missing from the Lamington lavas. Here, too, pumiceous material appeared in greater abundance in the later nuées ardentes. An increasing abundance seems characteristic of the end of explosive phases in eruptions of this kind, for at St. Vincent as well as at Mont Pelée similar distributions occurred.

Apparently the most highly gas-charged portions of the magma converted the lava directly into fine ash. Pumices and the pumiceous blocks which were present in the nuées ardentes resulted from a decline in gas tension and, at the lower end of the explosive scale, were porous blocks which intumesced during the descent of the nuée ardente.

In the Montserrat lavas Macgregor found that porosity increased with the proportion of residual glass. This relationship appears to hold with the pumiceous blocks from the nuée deposits at Lamington but it is not very obvious with the rocks of the dome. Some Type I. lavas do contain larger cavities than the more crystalline type lavas but little difference in the porosity of Type II. and Type III. lavas is apparent. It is interesting to find, however, that the more glassy green-hornblende-bearing Type III. lava contains microscopic vesicles which are usually absent from the other lavas. These vesicles are apparently indicative of the early stages of a gas phase that was halted by consolidation of the lava.

Accessories.

Apatite is the commonest accessory mineral. It is characteristic of all the dome lavas, but is absent from the old flow lavas of the western side of the cone.

W. B. Dallwitz has identified calcite and zircon in some of the andesites collected from the nuée deposits of the January, 1951, eruption. These andesites resemble the old lavas of the crater walls.

Opaque minerals.

Three rock types were examined by W. M. B. Roberts for opaque minerals. The first two, which were found as boulders in the beds of the Ambogo and Embara Rivers, probably originated from dykes, though they were never discovered in situ. One was a coarse-grained greyish non-porous rock with phenocrysts of plagioclase, hornblende, and biotite up to 5 mm. wide; the other was a fine-grained dark-grey aphanitic rock with neither vesicles nor phenocrysts. The third was from the lava of the southern wall.

The coarse-grained rock contained euhedral to subhedral crystals of pyrite ranging in size from 0.03 to 0.6 mm. and an iron oxide partly altered to limonite. In the fine-grained rock pyrite occurred as irregular areas up to 0.6 mm. in size; small quartz grains formed marginal zones either inside or outside the irregular border of the pyrite. The south wall rock type contained magnetite, chromite, chalcopyrite, and a titanium-rich magnetite with properties midway between magnetite and ilmenite. The pyrite and chromite were possibly introduced by secondary hydrothermal activity.

Mineralogical Indications of Temperature.

Much careful laboratory work has been done on the changes that take place on heating hornblende and biotite, but the results seem to be of little help in providing a geological thermometer because the experiments have not been able to reproduce all the complications of the enclosing groundmass. Field occurrences of the different types of hornblende and their degree of alteration suggest that pressure, rate of cooling, and action of gases, as well as temperature, control the type of amphibole formed. With four possible variables associated with the formation of mineral types, only the very broadest generalizations can be made concerning the temperatures of the containing lavas.

Purely on temperature considerations, the condition of some of the minerals seems anomalous. For example, one specimen of the Type I. lava contains amphibole showing the opaque magnetitic resorption that according to laboratory work takes place around 1040-1100° C. (Wittels, 1952; Macgregor, 1937). But the maximum extinction angle, which experimental work shows to decrease to zero at 900°, is greater than zero for the amphiboles of this lava.

Day and Allen (1925) heated biotite in an atmosphere of H_2O and CO_2, and found that decomposition set in above 850° and was very rapid at 900°. If this is so, the mineral should show more advanced alteration than the associated hornblende at temperatures of 1040-1100°. But in fact it is generally found that the two minerals have reached comparable stages of decomposition or resorption; in some instances the biotite is less altered than the hornblende, as in the western and southern wall lavas.

In view of these anomalies and the complexity of temperature-time-pressure relationships, it does not seem valid to attribute specific temperature limits to any of the lavas on the basis of mineralogical characteristics.

Chemical Analyses.

The analyses listed in Table III. reveal little variation in composition in either the new lavas, the old lavas, or the individual parts of the new dome. The old flow lavas show the most variation from the average chemical composition (Nos. 2 and 4). They are 2 to 3 per cent. lower in silica and 1 to 2 per cent. higher in magnesia and lime.

The western wall flow (No. 4) contains the highest recorded amount of potassium. A specimen (No. 13) from the southern sector of the new dome has a composition similar to that of the flow lavas; it is lower in silica and slightly higher in magnesia and lime. This difference in composition was reflected in the generally darker colour of the lavas from the southern part of the dome, but the mineral constitution did not vary significantly from that in lavas from the other parts of the dome.

The composition of the ash deposited by the nuée ardente of 21st January is very close to that of the lavas, although it has a somewhat higher alumina content. As the other constituents do not conform with this variation, it is possibly due to a difference in analytical technique.

It is of interest to note that the analysis of the ash (specimen No. 18) which fell on Port Moresby reveals a slightly lower silica content and a higher iron and calcium content. The difference may be too small to be significant, but similar variations in the composition of the ash which in 1902 fell on the island of Barbados, 100 miles from St. Vincent, were attributed by Flett (1908) to the winnowing effect of the atmosphere; the less dense constituents of the ash were carried by the winds to even greater distances.

TABLE II.—CHEMICAL ANALYSIS OF LAMINGTON LAVAS.

—	Old Lavas.				New Lavas.											Average.	Inclusions.		Ash.
	1.	2.	3.	4.	5	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.	19.
SiO_2 ..	59.03	56.38	58.57	55.19	58.88	57.92	59.82	59.85	59.82	58.45	59.76	60.26	56.92	59.72	60.32	58.69	47.48	39.90	57.38
Al_2O_3..	16.52	15.64	16.29	15.69	18.20	19.48	18.14	16.29	17.27	16.24	16.83	15.78	16.05	16.19	17.51	16.36*	10.42	0.91*	17.91
Fe_2O_3..	2.70	1.70	2.39	2.72	2.91	2.74	2.97	2.83	4 64	3.17	2.56	2.62	2.67	3.67	2.72	2.86	3.52	6.4 (Fe₂O₃ + FeO)	3.15
FeO ..	2.31	3.44	1.87	3.02	2 52	2.71	2.95	2.05	0.50	2.30	2.30	2.36	3.12	1.58	2.02	2.24	4.97	(included above)	3.02
MgO ..	3.76	5.82	3.01	5.52	2.96	3.09	2.74	3.58	3.37	4.05	3.43	3.54	4.96	3.42	3.24	3.97	13.71	52.3	3.77
CaO ..	6.22	7.37	5.21	7.36	6.45	5.65	5.85	6.21	5 84	6.71	5.89	6.04	6.93	6.04	5.70	6.29	10.86	nil	6.86
Na_2O .	4.36	3.86	3.58	3.36	5.25	4.28	4.58	4.19	4.22	4.09	4.41	4.02	3.88	4.23	4.33	4.04	1.97	n.d.	4.83
K_2O ..	2.58	2.12	1.65	3.35	1.98	2.03	1.98	2.36	2.63	2.39	2.43	2.31	2.21	2.33	2.30	2.38	1.30	n.d.	1.86
H_2O+	0.09	trace	1.40	trace	0.28	0.77	0.12	trace	trace	trace	trace	0.12	0.11	trace	trace	0.14	trace	nil	..
H_2O-	0.06	0.62	1.09	0.82	0.34	0.36	0.31	0.06	0.04	0.01	nil	0.03	0.07	0.07	0.21	0.26	0.03	nil	..
CO_2 ..	nil	n.d.	nil	nil	n.d.	n.d.	n.d.	nil	nil	nil	n.d.	n.d.	n.d.	n.d.	nil	..	nil	n.d.	..
TiO_2 ..	1.30	2.12	1.01	1.84	0.38	0.39	0.44	1.61	0.79	1.14	1.30	1.46	1.22	1.04	0.87	1.31	2.44	trace	0.66
P_2O_5 ..	1.12	1.08	1.02	1.44	0.33	0.33	0.31	0.99	0.79	0.81	0.64	0.86	1.11	1.54	0.76	1.01	0.60	n.d.	..
SO_3 ..	0 12	0.06	2.88	0.13	n.d.	n.d.	n.d.	0 21	0.16	0.13	0.11	0.18	0.14	0.21	0.17	0.38	2.33	n.d.	..
Cl ..	0 22	0.09	0.09	0.09	n.d.	n.d.	n.d.	0.14	0.10	0.15	0.15	0.10	0.11	0.13	0.15	0.13	0.08	n.d.	..
MnO ..	0 11	0.09	0.09	0.14	0.11	0.08	0.09	0.14	0.11	0.12	0.09	0.11	0.12	0.10	0.11	0.11	0.18	0.11	..
	100.50	100.39	100.15	100.67	100.59	99.81	100.30	100.51	100 28	99.76	99 90	99.79	99.62	100.27	100.41	..	99.89	99.62	100.58

* Including P_2O_5.

1. Magnetite lamprobolite andesite from eastern crater-wall—central sector.
2. Magnetite lamprobolite andesite from eastern crater-wall—northern sector.
3. Green-hornblende andesite from southern crater-wall—central sector.
4. Pyroxene andesite from western crater-wall—northern sector, lowest flow.
5. Basal layer of andesitic ash from eruption of 21st January, 1951.
6. Top layer of andesitic ash from eruption of 21st January, 1951.
7. Pumiceous bomb from night eruption of 21st January, 1951. (Type III. lava.)
8. Type II. lava from northern face of dome, July, 1951.
9. Type I. lava from eastern face of dome, July, 1951.
10. Type II. lava from southern face of dome, July, 1951.
11. Type III. lava from northern face of dome, February, 1952.
12. Type II. lava from eastern face of dome, January, 1953.
13. Type II. lava from southern face of dome, January, 1953.
14. Type II. lava from western summit of dome, January, 1953.
15. Type II. lava from terminal spine of dome, January, 1953.
16. Average of analyses 1–4, 8–15.
17. Inclusion of anhydrite-bearing hornblendite.
18. Inclusion of forsterite.
19. Ash which fell on Port Moresby, 21st January, 1951.

Analyst—1–4, 8-18, A. W. Dye & Co., Sydney.
5-7. A. H. Debnam.
19 C.S.I.R.O. Division of Industrial Chemistry.

Sublimation-Products and Incrustations.

In spite of the readily detectable sulphurous gases in the emanations from the volcano, very little sulphur and other sublimation products have been deposited round the vents. They were not at all obvious until the temperature round the vents had fallen so low that the surface no longer vaporized the frequent rains, after which small and very scattered patches of white and, more rarely, yellow material were seen.

When field inspection of the crater became practicable, the apparent scarcity of sulphur was confirmed; gypsum was found to be a more abundant sublimation-product.

The minerals deposited differed according to the location of the vents. At the northern foot of the dome a very persistent group of small vents penetrated the floor of the avalanche valley and emitted gas, low in water content, at temperatures of about 400°. Samples of the thin crusts of red and white material formed around these vents were examined by Mr. A. D. Haldane, then of the Commonwealth Scientific and Industrial Research Organization. The white material was found to consist of aragonite with silica as a minor constituent, and the red of an aluminium phosphate with accessory ferric oxide. Vents located round the base of a group of spines that emerged from the talus apron about halfway up the eastern face of the dome emitted gases that contained more H_2O than those of the lower vents, and also a little SO_2; their temperatures ranged from 100° to 400° C. Invisible high-temperature gas was emitted from fractures in a massive spine block. It left no sublimate, but a bright red fluid had exuded from the fractures and solidified into a hard brittle material in the form of thin flow-wrinkled sheets and ropy fingers. The material contains very small crystals (0.1 mm.) and glassy fragments in a matrix of an unidentified mineral which at the surface formed minute rosettes of lustrous crystals. The lower temperature vents commonly had round them extensive mats of gypsum crystals which in places had a little sulphur deposited with them.

A white incrustation that was common on the rocks of this eastern fumarole zone and other parts was X-rayed by W. M. B. Roberts and proved to be alpha-cristobalite.

Around the vents on the southern sector of the dome, crystalline sulphur seemed to be the predominant mineral, and gypsum was very much less abundant. On the summit of the dome in January 1953, sulphur and gypsum crystals were being deposited in very small amounts by the escaping gases. A white incrustation, similar to the one identified as alpha-cristobalite, was the most common sublimation product.

Parts of the nuée ardente deposits from the March 1951 eruption remained hot for many months, and the gases from them deposited gypsum crystals on the undersides of large blocks that lay on the surface of the ash-flow. These white mats of fibrous crystals were found on blocks up to 3 miles from the crater. The mineral was undoubtedly deposited more extensively, but had only been preserved in favorable conditions.

LAVA TYPES AND MECHANISM.

The order of emergence from the vent of the various lava types seems to correspond to a broad progression in certain mineral characteristics. The green-hornblende-bearing Type III. lava of the ash, pumice and bombs was the first to emerge; it shows no alteration of its amphibole and contains the most calcic of the plagioclase. Type I. lava, bearing bright red-brown amphibole, from between the blocks of the terminal spine, was the last to emerge; it shows the high-temperature reconstitution of the amphibole and contains the most sodic of the plagioclase. In between these extremes was the abundant Type II. lava which formed the bulk of the final dome and contained the brown amphibole and a plagioclase of intermediate composition. Unfortunately the lava type of the first dome is not certainly known, but if the nature of the large blocks from the nuée deposits is taken as representative of its composition then it was formed partly of the lamprobolite and partly of the green-hornblende-bearing lava. Clearly the subsequent structure was so composed. In spite of evidence of overlapping in the order of emergence a broad zoning in the lava column of the volcano is probable. Our petrologists have expressed the opinion that the lava types are temperature variants of the same magma, the Type III. lava being the low and the Type I. lava the high temperature variant. This view introduces an apparent paradox in that the most active lava in the volcanic mechanism, the green-hornblende-bearing Type III. lava, has the lowest temperature and the inert Type I. the highest temperature. Thus the order of emergence is from low to high temperature lava types.

The idea of zoning in the lava column is a not uncommon method of explaining petrological distribution and volcanic behaviour. After studying the petrology at Montserrat, Macgregor (1936) concluded that the great explosions there had been initiated by a deep-seated highly gas-charged green-hornblende-bearing lava which was overlain by a lava of less explosive character containing brown and " resorbed " hornblende. Williams (1942, p. 155) found evidence to support the view that hornblende tends to break down in the shallower parts of the magma chamber.

Brouwer's (1920) observations on the Ruang lavas, on the other hand, suggest that in some instances amphiboles may only form in the upper part of the magma chamber where temperatures are low and volatile concentrations are high. This observation is more in keeping with Perret's conception of zoning in a closed conduit volcano. He envisages the migration and concentration of the volatile elements in the upper part of the magma chamber, where below an irregular roof they formed a " gas sheeted " zone containing both discrete and interconnected gas pockets (Perret, 1939). Many phenomena of the Lamington eruption could be interpreted in the light of such an hypothesis.

The conventional pattern of activity of the volcano with its early climax and declining explosivity suggests that we are dealing with a single energy system of a more or less homogeneous character. The gas tension in the magma chamber, having been built up to a critical point, breaks through the old and well solidified conduit and produces an outburst of Plinian magnitude. Perhaps this eruption voids the principle of a gas-charged pocket, or pockets, immediately adjacent to the conduit. The more distant pockets are held for a short time by the inertia of the viscous magma, and then follow adjustments to re-establish equilibrium in the deep-seated energy system. These adjustments probably involve both the vertical and lateral movements of the magma; the viscosity of the lava body is such that earthquakes and tilt changes are a prominent feature. When these movements are strong and fluctuating the explosive potential of the volcano is high. A decline in this intensity accompanies the transition to quiet effusion.

The idea of a petrological zoning in the magma column makes the order of emergence of the lava from low to high temperature types more reasonable, especially if it is assumed that volcanic heat is derived from sources at depth. In this connexion Verhoogen has suggested that much of the requisite volcanic thermal energy may be derived from juvenile gases rising from the deep interior (Williams, 1954). It seems therefore possible at Lamington that the upper part of the magma column was occupied by a highly gas-charged green-hornblende-bearing lava which supplied the energy for the great explosions and much of the effusive activity. The early large-scale energy releases were followed by a movement of magma into the conduit, some of it rising from a deeper, higher temperature source and forming the lamprobolite-bearing lava types. At the same time there must have been lateral migrations of the gas-charged Type III. lavas, for they contributed abundantly to the material of later explosions. The Type III. lava last appeared after the abortive eruption of June 1951, when it emerged from the centre of the dome and extended the northerly dimensions of the structure. The later extrusions were apparently all of the lamprobolite-bearing lava types which show evidence of higher prevailing temperatures.

Much more detailed work is necessary on eruptions of this type to bring discussions of mechanism to a less speculative plane.

SEISMIC ACTIVITY.

Volcanic earthquakes were a notable feature of the whole eruption of Mount Lamington. Not only was the early climactic eruption heralded by earthquake swarms, but subsequent explosive activity and the long-continued dome-building phase were associated with periods of fluctuating seismic activity.

The installation of a seismograph on 7th February 1951 enabled earthquake phenomena to be studied in detail. Earlier observations had been dependent on " felt " earthquakes and, inevitably, data are incomplete, particularly in the smaller disturbances. The instrumental data brought to light some interesting relationships which will be discussed later.

TECTONIC EARTHQUAKES.

Inhabitants pointed out that earthquakes were not common in the area during normal times; and examination of the general regional seismicity over recent years confirms this. Since 1910 earthquake epicentres lying close to the Papuan volcanic arc have been established for the following positions:—

EPICENTRE.

Date.	Latitude °S.	Longitude °E.
21st May, 1913	8.5	149.0
11th October, 1913	9.0	147.5
29th October, 1917	8.5	149.0
21st March, 1919	8.5	149.0
10th November, 1939	9.4	148.9
7th June, 1940	9.7	151.5
24th September, 1941	9.0	153.0
22nd October, 1947	10.0	151.5
5th October, 1953	9.3	152.5

The earthquakes of this period do not appear to be of exceptional magnitude, but they were apparently large enough to be recorded at a number of international seismic stations. The foci were generally shallow. Compared with the more active volcanic arcs of New Guinea this seismic activity is slight, and it is probably significant that the vulcanicity of the area appears to be of a correspondingly low order.

In considering the distribution of these epicentres it is noted that those of 1913 to 1919 occur towards the western end of the Cape Vogel Basin. Twenty years later, i.e. in 1939, an earthquake occurred a few miles south-west of Mount Victory near the central part of the Basin, and two further earthquakes, at the eastern end, followed in 1940 and 1941. This second group of shocks preceded the eruption of Goropu volcano in 1943, which was heralded by numerous small local shocks during the two years before the outburst. A single shock at the eastern end of the arc, in 1947, was the only other indication of tectonic movement before the eruption of Mount Lamington in 1951.

Data on tectonic earthquakes elsewhere in the New Guinea region reveal a pattern with a marked fluctuation in frequency, as if the region were subjected to a periodic crustal stress pulse which produced a " seismic fever ". Reactivation of volcanic centres often followed such pulses. This is suggested by the limited data available on the powerful eruptions of the late 'thirties and early 'forties, and corroborated by the extraordinary eruptions of the 'seventies and 'eighties of the previous century. It is interesting to note that the earthquakes in the Papuan zone during 1939 and 1941 appear to be local expressions of a stress pulse which had found widespread manifestation throughout New Guinea during the 'thirties. The violent eruption from a new vent in the Goropu Mountains in 1943, therefore, seemed more than coincidental when it is remembered that there had been a hiatus of twenty years in local earthquake activity. The solitary earthquake in 1947 at the eastern end of the zone, however, does not seem to be sufficient prelude to the eruption of Mount Lamington in 1951.

If the long-dormant and well-plugged Lamington volcano is regarded as an isolated system of forces in which a cooling viscous magma had built up a large store of highly compressed volatiles, it does not seem unreasonable to suggest that, once again, a change in stress conditions may have played a part in initiating the eruption. First, a group of earthquakes, 1913-1919, suggests the possibility of movement in a north-east trending fault which may have been a controlling structure of the volcano; the earthquakes of the 1939-41 period suggest movement in the north-west structural elements of the region. The Goropu vent lies at the foot of a fault scarp with a north-west trend; the 1939 epicentre between Lamington and the Goropu vents could have been related to movement in this fault. Inhabitants in the area reported numerous earthquakes during the two years before the Goropu eruption, but the shocks were felt over such a wide area that many were probably tectonic rather than volcanic in origin. Thus, the 1939 earthquakes seemed to indicate the beginning of protracted tectonic movement less than 80 miles south-east of Lamington and in a south-easterly-trending structure. The effects of this movement may well have had north-westerly extensions which disturbed the Lamington system. Tensional or compressional forces would tend to upset the equilibrium conditions in a gas-charged magma, thus setting in motion a train of events which eventually removed the constraining plug material and culminated in the powerful eruption. With slow-moving viscous magma and constraining conditions which had been static for a long time one should expect to find a lag of some years rather than an immediate response.

If the Lamington volcanic system was isolated and uninfluenced by variations in regional stress, its beginning during another stress pulse which appeared to cause a widespread increase in regional seismicity was merely coincidental.

In 1949 and 1950 the number of earthquake epicentres in the New Guinea region was twice as great as that for the two previous years, and the number of definite shocks increased still more during the early 'fifties. The unusually powerful eruptions of Bagana in 1950, and of Lamington in 1951, the reactivation of the old centres of Long Island and Tuluman in 1953 (Reynolds & Best, 1957) and of Langila volcano in 1954 (Taylor, BeBst & Reynolds, 1957), coincided with this seismic fever. It seems, however, that these conditions did not obtain in the New Guinea region only, but also in the Solomons and the New Hebrides, which are the natural south-easterly extensions of this tectonic zone. In December 1950 Ambrym volcano in the New Hebrides began an unusually powerful and protracted eruption which followed a year of rapidly increasing regional seismicity. Submarine eruptions in the New Hebrides and the Solomons followed. Increased vulcanicity in New Guinea has frequently had its counterpart in the New Hebrides. This was certainly so in 1888, when both Ritter Island and Ambrym produced remarkable eruptions and, more recently during the 'thirties, the activity of Manam and the Rabaul volcanoes corresponded with marked activity from Ambrym. The milder eruption of Ambrym in 1942 appears to have a counterpart in the 1941 eruption at Rabaul and in the 1943 eruptions of Goropu; and the Lamington eruption began within six weeks of that of Ambrym.

Unless there is an underlying stress condition to explain this pattern of events we have a very unusual set of coincidences. Little account is taken of the magnitude of the shocks involved when postulating that a change in the number of regional earthquakes per year is due to a stress pulse. This theory is open to criticism but, at the same time, the subject is worthy of greater attention.

THE INITIAL EARTHQUAKE SWARMS.

Until about a week before the eruption, the only seismic disturbance which seems to be remembered with any clarity by local people occurred in the first week in December. On 5th December 1950, an intermediate focus earthquake of magnitude 7-7¼ occurred near the southern end of New Ireland. This was the probable origin for the shock felt at Lamington, for later in the year similar distant shocks were felt quite strongly in the area.

According to accounts given by observers at Higaturu, the swarm-pattern earthquakes began abruptly at 1600 hours on Tuesday, 16th January 1951. Two observers from the Sangara area, however, make unspecific reference to occasional shocks occurring three or four days before, which may have been the cause of the landslides noted in the crater on Monday.

The frequency of the tremors increased rapidly. By Wednesday, they were occurring at seven-minute intervals, and on Thursday they were described as almost incessant; on Friday and Saturday frequency appears to have reached a peak, and fell abruptly on Saturday night. Observers make no reference to shocks on Sunday morning and Miss de Bibra's remarks (p. 18) suggest that the earthquakes had ceased during the hours before the great explosion.

The intensity of the earthquakes appears to have been small at settlements 5 miles or more from the crater. At Higaturu small unstable objects in the houses kept falling and doors and windows rattled but no damage was done. Small cracks appeared in the dry roads and paths, otherwise there was no visible evidence of ground movement. Closer to the crater there seems to have been a rapid increase in intensity. Villages between Issivita and the crater suffered damage and Father Porter reported an exceptionally severe shock at one of the nearer villages on Friday, 19th January. Less reliable reports of natives suggest extraordinary seismic movement in this area, and parties approaching the crater from Higaturu noticed that intensity increased rapidly as they neared the mountain. On Thursday, native police climbing to investigate the crater were frightened by the intensity of the earth movements and returned, and on Saturday Europeans reported that to remain standing during the severe shocks was impossible. Intensities such as this were probably felt not more than 2 miles south of Higaturu.

The distribution of intensities throughout the area showed a similar rapid decline with increasing distance from the crater. The living quarters at Sangara Plantation were only 3 miles beyond Higaturu, and yet so marked was the decrease of intensity over this distance that Mrs. Cowley spent Saturday night at Sangara because earthquakes made sleep impossible at Higaturu. West of the volcano, at the more distant centres of Awala and Wasita, earthquakes were also less severe. One observer remarked that the earthquakes at Waseta were of about the same intensity as those at Issivita, but this generalization is considered to be based on a very short period of observation at Waseta. No earthquakes were reported at Jegerata on the north-eastern slopes. As this village is only 10 miles from the crater this appears anomalous unless the foci of the disturbances were on the opposite side of the cone and were being damped out by distance. Alternatively, Jegerata may belong to a seismicly " dead " area. Later in the eruption, however, numerous small shocks were felt at Popondetta, which is in the same azimuth as Jegerata, so that the absence of preliminary earthquakes at Jegerata does seem anomalous.

The individual tremors of the earthquake swarms appear to have been of two types. The more common type was of short vibration which built up quickly to a maximum and gradually faded away. The duration of perceptible movement for the larger tremors was probably not more than ten seconds. The period of vibration seems to have been relatively slow at Sangara Plantation and Waseta, for descriptions suggest a rocking movement rather than a sharp vibration. Occasional tremors had very long periods and appeared to be exceptional types of movement. At Higaturu Mrs. Cowley observed: " Between Friday and Saturday evening we experienced four movements of a different type; the vibration or tremor seemed to cease for a few seconds whilst the house seemed to rise and fall slowly and smoothly like a ship riding a wave ". Observers at Sangara and Waseta also mention a similar type of wave motion. Anderson and Flett (1903) have observed that the precursory earthquakes of the 1812 and 1902 eruptions of St. Vincent had a curious undulatory movement which was quite different from the normal regional earthquakes. The preliminary earthquake development at Lamington followed the pattern which is the rarely realized " ideal " seismic warning of a great eruption. At Pelée, in 1902, notable preliminary earthquakes swarms did not occur but the crater activity began a fortnight before the climax. At St. Vincent, the small local earthquakes had begun two years before and the climax came within 24 hours of the first signs of activity in the crater.

THE SWARMS CONTINUE.

After the climactic explosions on Sunday, 21st January, the earthquake swarms began again as a prelude to further explosive and effusive activity. Only meagre data are available concerning the period from 22nd January to 7th February, because

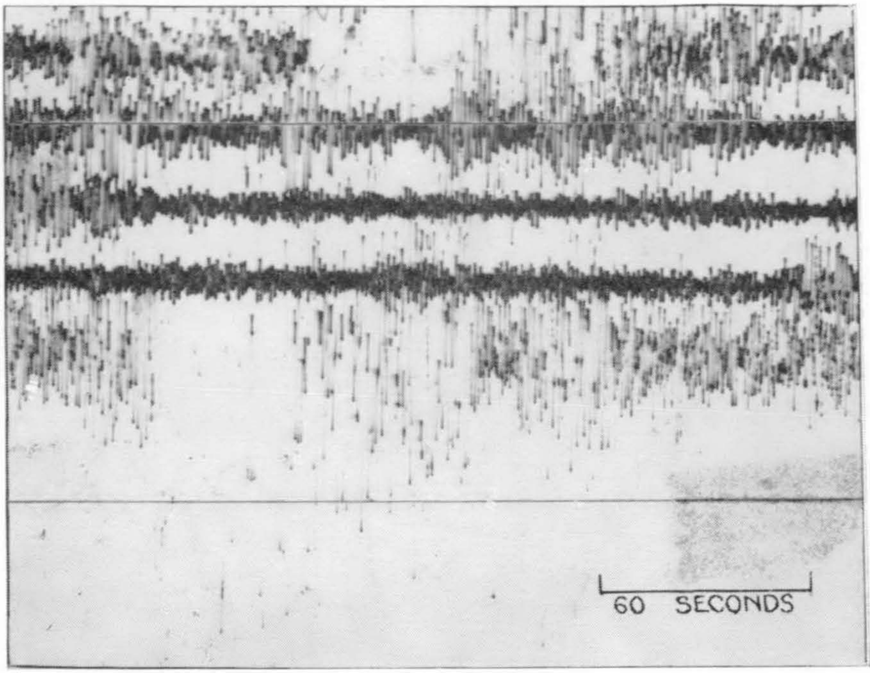


Fig. 147. 18.2.51.

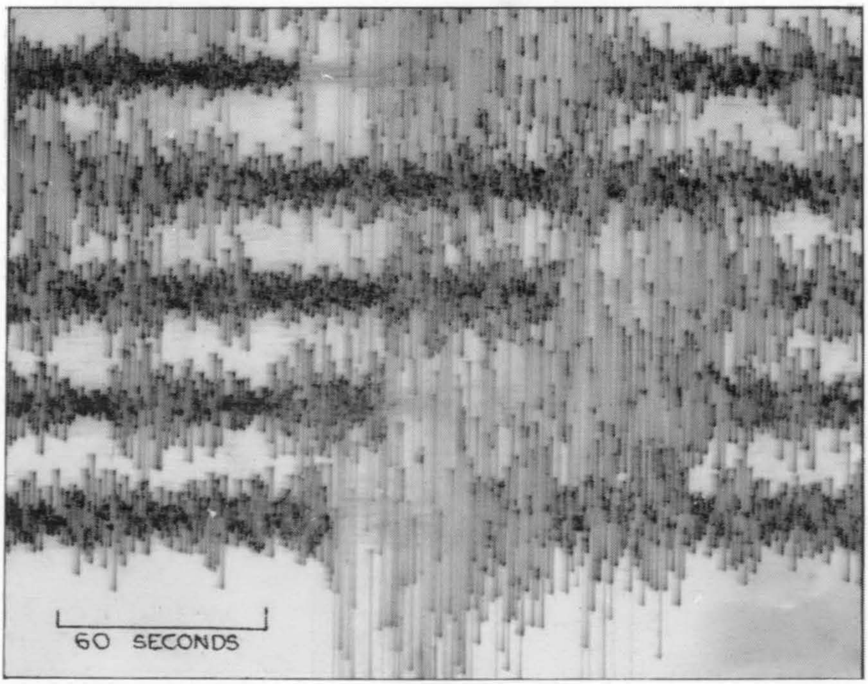


Fig. 148. 22.2.51.

[*To face page* 88.]

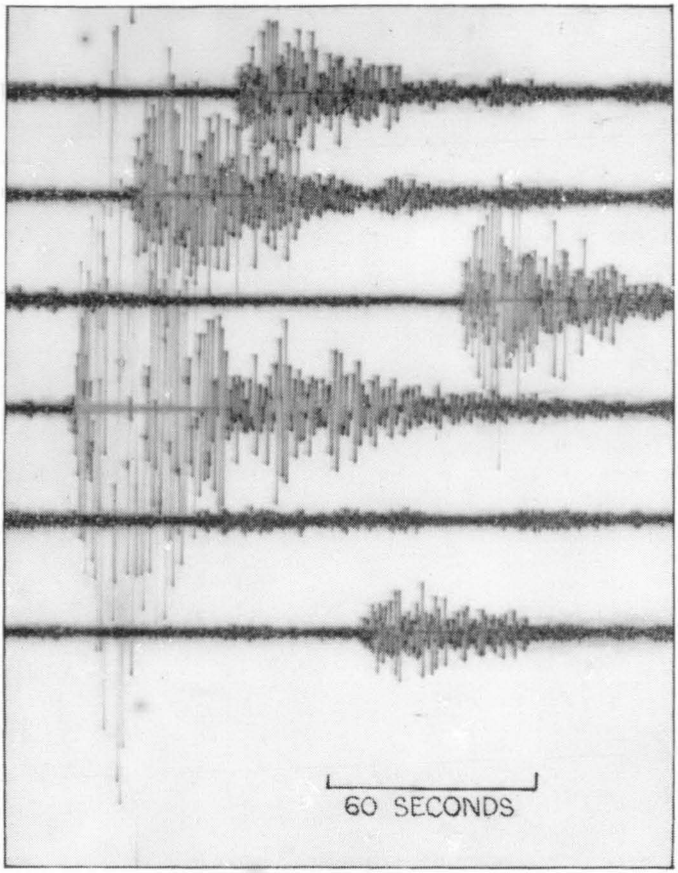


Fig. 149. 21.2.51.

Fig. 150. 5.3.51.

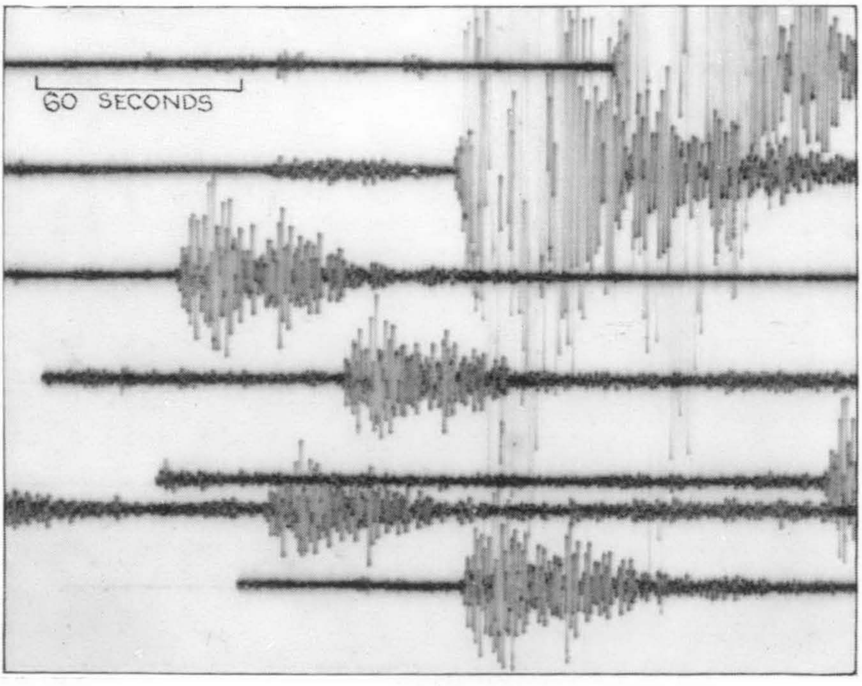


Fig. 151. 24.2.51.

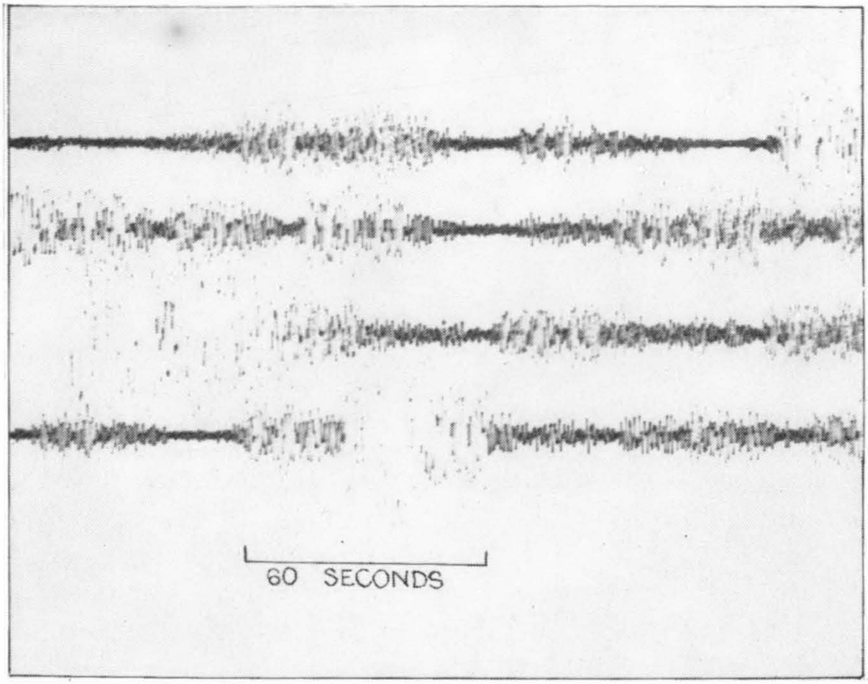


Fig. 152. 11.2.51.

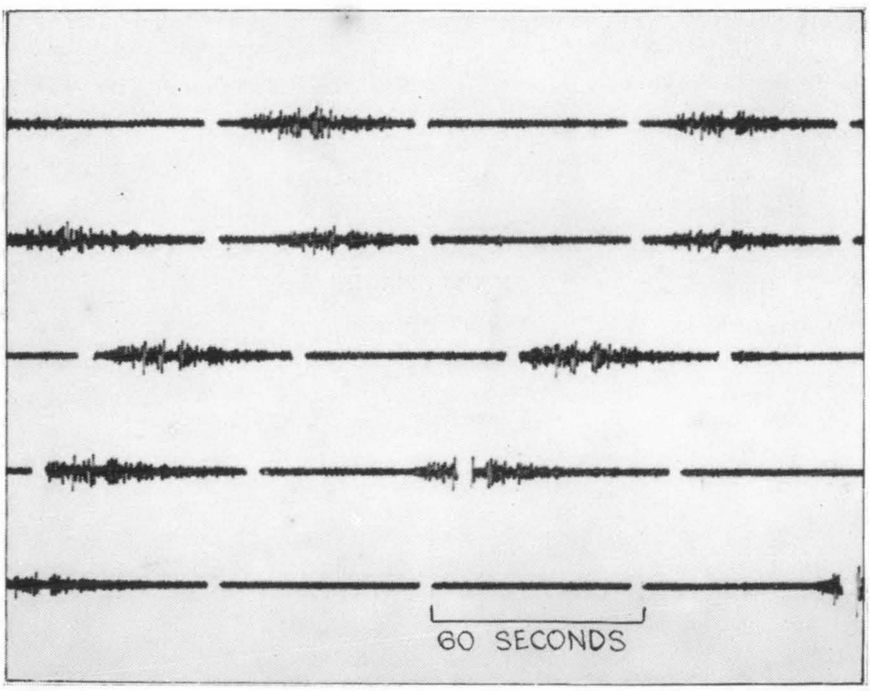


Fig. 153. 7.3.51.

no one remained living in an area within 10 miles of the crater during this time. Information is therefore limited to shocks felt at relatively distant settlements and to the observations made by the few people who visited the zone of devastation. Such observations as the writer was able to make at Sangara Plantation and elsewhere supplemented these.

Seismic activity, if it had actually ceased, began again on the day following the great explosion. Mr. Morris, a keen observer, was moving through the devastated villages near Issivita when he noticed that " the ground had a constant, even vibration; immeasurably slight ". This is a most interesting observation for later when the seismograph was installed at Sangara a constant microseismic movement was recorded. It is not improbable that this " harmonic tremor " was characteristic of the whole period covering the fortnight after the climax. The final analyses of these instrumental data suggested that this feature indicated a high explosive potential.

Confirmation of this important observation soon came. Small earthquakes began to be felt once again at more distant locations and explosive activity was resumed. On 24th January, a field party in Higaturu felt several small earthquakes, and at 0300 hours on 25th January a powerful explosion projected ash and steam to many thousands of feet. At 1500 hours the following day a steam explosion occurred. The relationship looked promising; perhaps earthquakes would continue to warn of coming explosions. That night from 2000 hours to 0630 hours observations of the prevailing seismicity were made at Sangara Plantation. The shocks were numerous but most of them were of very small amplitude. During the night fifty-one earthquakes occurred, and up to 0300 hours many rumblings were heard from the crater.

The next night, 27th January, a larger explosion occurred immediately after numerous small earthquakes which were felt at Popondetta. Loud sustained rumbles from the crater started at 2200 hours and at 2245 hours tremor swarms began. Between 2245 and 2305 hours the shocks were almost continuous and, in addition, a long wave motion of relatively slow period was perceptible. It resembled a surface ground wave. At 2319 hours a stronger shock lasted two minutes and ended with a loud rumbling from the crater. The swarm pattern continued until 2336 hours, when a large explosion burst from the crater with a loud rumble. The activity continued until after 0100 hours when the volcano was concealed by cloud. No further earthquakes were felt that night.

This further confirmation of the importance of earthquakes in indicating approaching explosions resulted in observations being made at Sangara Plantation whenever possible (fig. 13). Observations and reports suggest that a fluctuating pattern of earthquake swarms was characteristic of this phase of intermittent explosive activity; it seems unlikely that the seismicity ever reached the proportions attained by the pre-eruption build-up.

THE INSTALLATION OF THE SEISMOGRAPH.

A Wood-Anderson seismograph was installed at Sangara Plantation early in February and recording began on 8th February. The instrument was 8.5 miles from the crater. A magnification of 2800 and a pendulum period of 0.8 seconds were adopted for recording purposes. The instrument was not designed for such near-focus earthquakes and initially a slow photographic paper gave poor records. Later, a faster paper was obtained and the records improved greatly.

In the field, a rough graph of the number of earthquakes against time was plotted to keep track of seismic trends. This seems to be an unsatisfactory expression of seismicity because the tremors ranged in amplitude from less than 3 mm. to over 30 cm. In a more detailed final analysis of the records an attempt has been made to find an expression of the total seismic intensity by taking into account the amplitude of the tremors. The shocks were divided into five arbitrary classes:

Class	1	18 cm.	up	to	30 cm.	maximum	amplitude.
,,	2	6 cm.	,,	,,	18 cm.	,,	,,
,,	3	3 cm.	,,	,,	6 cm.	,,	,,
,,	4	1.1 cm.	,,	,,	3 cm.	,,	,,
,,	5	0.3 cm.	,,	,,	1.1 cm.	,,	,,

To obtain a figure for the total intensity the number of shocks in each class was multiplied by an average amplitude, which was taken as 24 cm., 12 cm., 4.5 cm., 2 cm. and 0.7 cm. respectively, and the results added. The seismic data have been expressed first as a daily rate to give a broad picture of the activity during 1951 (fig. 154) and secondly as an hourly rate during the most highly explosive phase, to show the relationship between earthquake fluctuations and explosive outbursts (figs 13-20).

The broad picture of seismicity given by the graphs of the tremor frequency and seismic intensity indicates a high, varying rate of continuous seismic activity during the period of highest explosive potential and a much reduced, spasmodic pattern during the long continued effusive phase. The rate falls rapidly as the gaseous accumulations are successively released; it fell to a very low level after the major eruption of 5th March which partly destroyed the dome. It then rose quickly to form a broad irregular peak in mid-March, a period of dome extrusion, and fell again to negligible proportions in the first week in April. The last fortnight of April brought a swarm of unusually small earthquakes which faded into a low daily rate by early May. Almost two months elapsed before the rate increased significantly. For a few days the seismic activity rose sharply to a peak on 28th June and fell again more rapidly to a low daily rate. The next seismic development, which began in the second week of August, had a different pattern from those occurring earlier. Instead of rising rapidly to a sharp peak and declining relatively quickly the tremor frequency rose slowly, reaching a broad peak about a month later, and then declined very slowly over a period of many months. The slow decline continued over most of 1952.

DOME BUILDING RELATED TO SEISMIC ACTIVITY.

The dome was extruded most rapidly during the early stages of the eruption when seismic activity was highest. Later seismic developments appeared to be accompanied by either collapse or stationary conditions rather than by uplift. Periods of growth, however, do seem to follow a recrudescence of seismic activity, as if the earthquakes were symptomatic of transfers of potential energy to places at depth where they eventually found manifestation as extrusive activity. This is particularly obvious during the rapid dome-building phase which followed the earthquakes at the end of June. It will be noted that the occurrence of tremor swarms in August initially heralded collapse in the dome. Not until the seismic activity began to decline did the dome rise again. In keeping with the pattern of seismic activity this uplift was long continued. Three months elapsed before it reached a maximum, after which extrusive activity declined slowly.

EXPLOSIONS AND SEISMIC ACTIVITY.

Detail of the relationship between the earthquakes and explosive activity of the month ending 7th March 1951 is illustrated by graphs (figs. 13-20). Except in periods of extreme seismic activity, when the intensity of movement made the records illegible, the graphs have been smoothed by plotting the average for three consecutive values at each hourly point.

Beginning on 8th February with seismic frequency of 60 tremors per hour, the graph exhibits a trend of gradual decline, upon which a fluctuating pattern of peaks and troughs is superimposed. Major peaks in seismic activity occur on 18th, 19th, 22nd February and 2nd March. The occurrence of major explosive outbursts on 18th, 22nd, 24th February and on 5th March suggest a close relationship between the two phenomena, but even during this period, when the explosive potential was high, a major spasm of energy release at depth was not always followed closely by an explosive outburst. No major explosion was recorded between 18th and 22nd February, and a growing lag is evident between consecutive events. The eruption of 18th February occurred soon after a seismic peak, whereas the eruption of 5th March lagged three days behind the previous peak. It is also noteworthy that the magnitude of the eruption may be independent of the height of precursory seismic peaks; the fluctuations from 18th February to 2nd March decline in amplitude, yet the eruption of 5th March, which followed the lowest peak, was by far the largest of this post-climax group of explosions. Irregularities in the relationship between seismic and explosive activity are more understandable if it is remembered that explosive activity is only one avenue of release for volcanic energy. With a viscous magma an enormous amount of energy may be expended in the form of earthquakes, or uplift and tilting of the surrounding crust, as well as in the extrusive and heat-maintaining processes. It is to be expected that a dome-plugged conduit would inhibit rather than facilitate the movement of highly gas-charged portions of the magma, so that, if the movements at depth are not extraordinary, lags and accumulations of explosive energy may take place. Considering that, at basaltic volcanoes, eruption may lag several weeks behind seismic maxima, the association of the two events at Lamington is very close (Finch, 1943).

The seismic records at Lamington exhibited two principal types of movements: a continuous ground movement of the pulsation type and a discrete earthquake of various forms. The pulsation type of movement has been reported as a common feature of the Strombolian activities of many of the Japanese volcanoes and it has also appeared in connexion with the effusive activity of the Hawaiian volcanoes. It is not common, however, with andesitic and dacitic volcanoes (Minakami, 1951, p. 12). At Aso volcano continuous-train earth pulsations occurred for 100 days before the paroxysmal outburst on 25th December 1959, and immediately before the outburst the amplitude of these vibrations fluctuated over a wide range. At Miyakesima volcano, on the other hand, both continuous pulsations and discrete earthquakes occurred before the explosive activity, and after it began the pulsations increased in amplitude and the normal discrete volcanic earthquakes ceased. Minakami (1941) considered normal earthquakes to be due to activity of the magma at depth and the pulsations to be caused by activity of the magma which ascended into the superficial parts of the conduit. It is clear from these examples that pulsations of the continuous type can precede and accompany volcanic explosions. Explanations of the phenomena vary from vibration of laminae in the cone structure (Omer, 1950) to magma oscillation and external and internal eruptions (Sasa, 1936).

At Lamington the pulsation tremors were essentially a feature of the early period of recording, when conditions were ripening for further paroxysmal outbursts. The movement was very prominent when recording first began and, with some fluctuations, remained so until the eruption of 18th February (fig. 147). After this explosion, except for a marked prominence during the seismic peak periods (fig. 148) the pulsations became negligible (fig. 149). The paroxysmal eruption of 5th March, however, was accompanied by a continuous ground vibration which lasted 58 minutes (fig. 150): the movement of the ground during this period was so severe that little other than the tapered tail of this disturbance was recorded on the photographic paper. This was the only instance in the course of the post-climax eruptions in which an explosion was accompanied by a very distinctive ground movement. The shallow-pocket eruption of 24th February exhibited a slight microseismic movement which lasted a few minutes (fig. 151), and the small outburst of 11th February was accompanied by the normal volcanic earthquakes and the usual microseismic movement which was characteristic of this period (fig. 152).

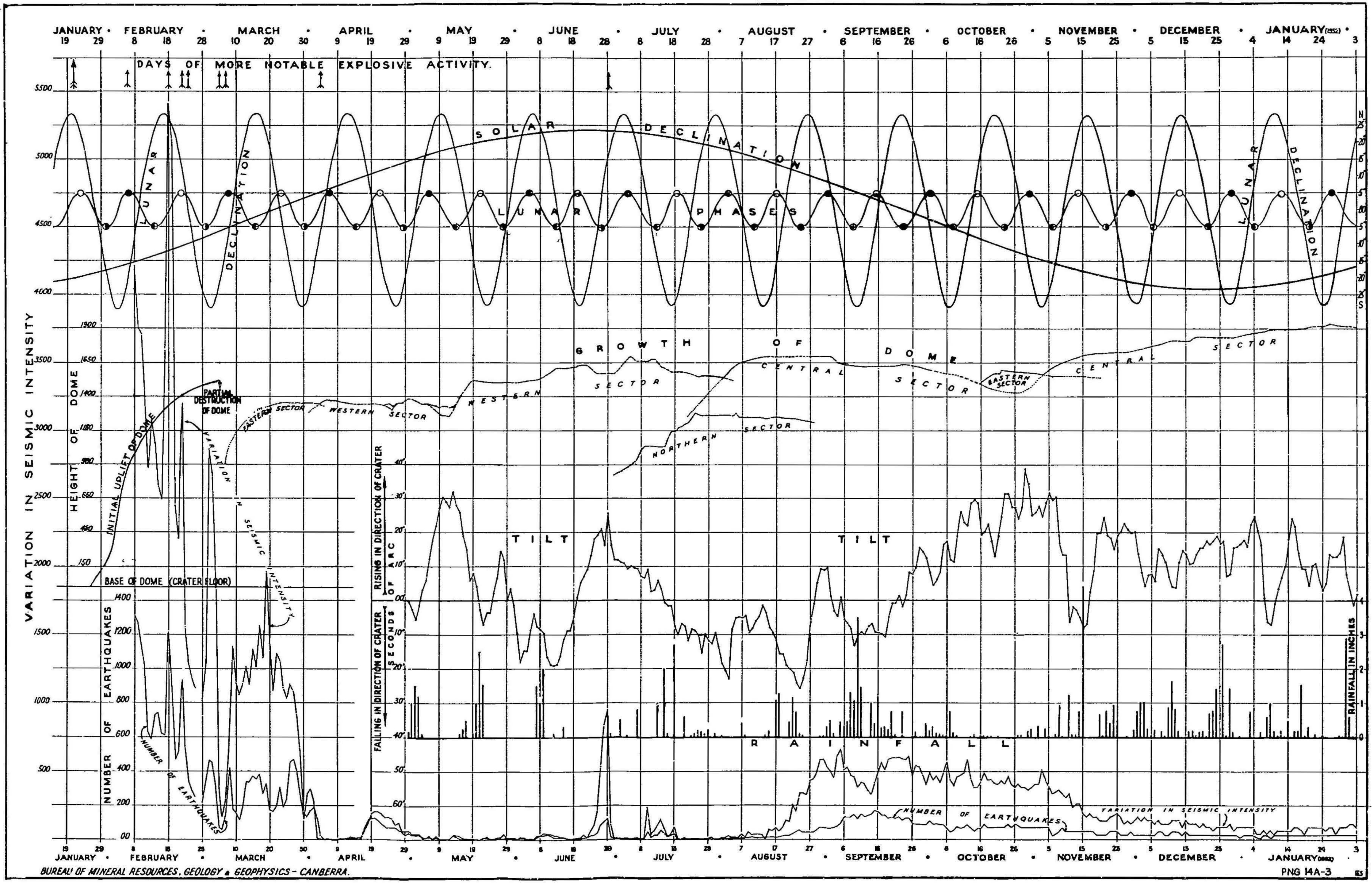
The form of the discrete earthquakes which originated from the volcano seems to vary largely with the magnitude of the shock. The large shocks begin with a small-amplitude preliminary tremor of about 2 seconds duration and then the amplitude rises to a steep peak from which it falls smoothly to a tapered end. Some of the shocks last longer than two minutes. The small tremors have an amplitude peak which tends to become flatter (figs. 149 and 151), and the very small shocks seem to be more or less amorphous. The large shocks resemble in shape those recorded at Usu and Asama volcanoes in Japan (Minakami et al., 1951). Minakami considers such shocks to be normal volcanic earthquakes which occur at depth, and draws attention to the formal similarity existing between this type of shock and small tectonic shocks recorded close to their epicentre. The Lamington earthquakes, however, differ, in one important respect; the maximum amplitude occurred up to 20 seconds after the beginning of the shock instead of abruptly after the end of the brief preliminary tremor identified as the P phase. Dr. P. L. Willmore, in a personal communication, has suggested that this late development of the peak may be due either to protracted disturbance at the focus or the masking of part of the P waves by irregularities such as a triggering shock or movement of energy along short-time paths.

Apparently multiple and protracted origins, local resonance, complex travel paths, and variation in travel times of the wave motion may all contribute to the form and characteristics of a volcanic earthquake and add to the difficulty of interpretation. Some of the Lamington shocks have more than one amplitude (fig. 151) and are not unlike the form of tremor Minakami classified, at Usu volcano, as a dome-building type. Since much of the dome movement at Lamington was unaccompanied by seismic activity the dome growth cannot be connected with a specific type of tremor.

The March eruption which marked the end of the most highly explosive phase of the volcano's activity also introduced a change in the earthquake pattern. The afternoon of 5th March was the first earthquake-free period since recording began. Occasional shocks began that night and continued during 6th March. On 7th March, swarms of small, remarkably regular, earthquakes began (fig. 153). These shocks gradually increased in amplitude and their numbers decreased. By 9th March, the earthquakes were predominantly of class 2, large amplitude category. Three days later the small tremors were reintroduced and for the remainder of the month the

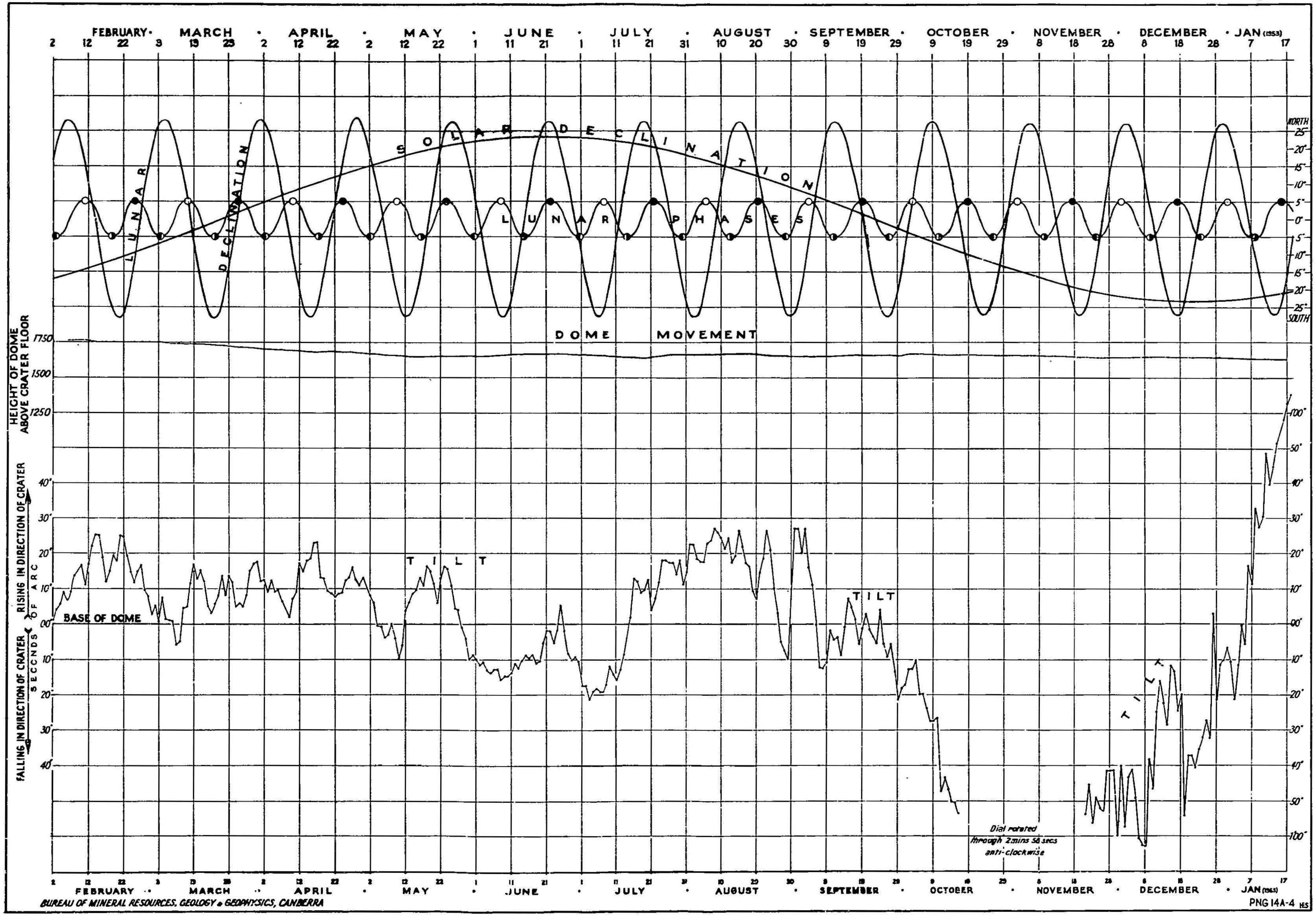
DAILY INSTRUMENTAL DATA AND LUNI-SOLAR DISPOSITIONS - MOUNT LAMINGTON 1951

Fig 154



DAILY TILT AND DOME VARIATIONS - MOUNT LAMINGTON 1952

Fig 155



frequency and the amplitude of the shocks fluctuated considerably (fig. 154). These seismic variations were accompanied by vigorous growth on the eastern side of the dome and by an explosive eruption of small size and uncertain date. Small explosions also took place early in April and late in June. The waning spasms of seismic activity were accompanied by correspondingly small-scale explosive phenomena, and the earthquakes of the last half of the year were associated entirely with extrusive activity.

TILT.

Magmatic pressures associated with volcanic activity, in addition to causing earthquakes, can produce a change of level and marked tilting near a volcanic vent. The effect is most pronounced with viscous acid and intermediate lavas, but may be also appreciable with fluid basic lavas. This aspect of volcanic behaviour has received particular attention from vulcanologists because of its value as a prediction aid. Study of the relationship between the tilt changes and explosive activity of the andesitic Asama volcano in Japan revealed close correlations which enabled Minakami (1942) to calculate a forecast function to give, up to two months in advance of their occurrence, the order of magnitude of coming explosions. At the Hawaiian volcanoes, tilt measurements have been carried out for many years, and although the tilt effects are much less pronounced for this effusive basaltic magma, tilt variations have sometimes proved a valuable aid to prediction. When Mauna Loa erupted in 1950 (Finch and Macdonald, 1953) abnormal tilt was recorded 22 miles from the crater. Although most of the explosive activity had ended at Lamington when a tiltmeter was installed, the records of the later period suggest that tilt was a conspicuous feature of the eruption. The single-component, spirit-level instrument set up at the Observation Post was oriented in the direction of the crater, almost north-south. Daily readings from the instrument during 1951-52 have been graphed (figs. 154 and 155), but interpretation of the results is handicapped by lack of knowledge of the normal annual pattern of tilt for this site. Seasonal variations in crustal movement can be caused by gravitational influences of the sun and moon, by changes in temperature and pressure distributions, and by rainfall (Tomascheck, 1952; Finch and Macdonald, 1953). In the composition of the tilt graph mid-day readings have been used in order to eliminate, as far as possible, irrelevent fluctuation due to temperature. The rainfall data plotted for 1951 do not show a consistent relationship with the tilt movements. Whatever the influence of seasonal and meteorological factors on the tilt pattern, movements of volcanic origin appear to predominate.

The graph moved through a range of 65 seconds during 1951, and towards the end of 1952 fluctuated over several minutes. Ignoring the minor movements during 1951, there are three broad fluctuations, with peaks in mid-May, the end of June, and late October. These movements seem to be related to the volcano's extrusive activity, as the general trend is for the dome to remain stationary, or show signs of collapse, during periods of rising tilt and to grow vigorously with a falling tilt.* The sharp rise to the May peak is accompanied by a collapse of the western sector of the dome, and the fall in tilt introduces a corresponding uplift. A similar pattern is suggested by the June peak, when the collapse is not so well defined but a vigorous uplift of the northern and central sectors of the dome is accompanied by falling tilt.

* Uplift in the direction of the crater is referred to as a rising tilt and vice versa.

The October rise in tilt has different characteristics from previous fluctuations. The rise is slow, the fall slower, and minor fluctuations are more prominent. The change in tempo begins after June, and is not unlike the phase change in a seismogram where a longer-period wave train is introduced. It is fitting that this change in rhythm should be introduced at the close of the explosive phase of activity; it is a pattern to be expected during the declining period of an eruption, when stored energy, having found its most vigorous expression in the early explosive release of more mobile volatiles, finds its final expression in a long continued slow extrusive activity.

Seismic and tilt patterns for the end of 1951 resemble one another both reflecting the slower rhythm with a gradual rise and fall, and, if the minor tilt fluctuations are smoothed out, both begin to rise about the same time. In detail, a suggestive similarity exists between the tilt and seismic intensity graphs from 27th August to the 15th November. Uplift of the mountain block is accompanied by earthquakes of larger magnitude, and the sharp drop in tremor magnitude, early in November, coincides with a sudden trough in the tilt. The tilt pattern rises again to begin a series of fluctuations which appear unrelated to the seismicity except that, in the broad trend, both are falling slowly, the seismic activity more definitely than the tilt.

The broad tilt pattern for 1951 suggests that the prelude to extrusive activity is a build-up of subterranean pressures beneath the cone. These pressures lift the mountain block over a wide area and as they are released by dome extrusion the block subsides. This interpretation is simplified and is suggested with reservation. It must be remembered that the tilt data are derived from a single-component instrument installed in far from ideal conditions more than 8 miles from the crater; in addition, the normal seasonal fluctuation of tilt is unknown. Nevertheless the trends outlined above appear to be consistent.

Relationships during 1952 are not nearly so clear. Dome movement during this period is comparatively slight and, for the most part, involves a gradual collapse with minor, poorly defined, periods of uplift. Until the end of May, tilt fluctuates through an amplitude little more than half that for the corresponding period in the previous year. Then in early June and early July, adjacent troughs precede a rise of more than 45 seconds to a broad peak. The tilt then fluctuates through a range of more than 30 seconds for two weeks as if in unstable equilibrium. It then remains relatively stationary around zero for about three weeks. Finally, in early October it plunges through an extraordinary range of about four minutes.

The movement indicated by this fluctuation in tilt is possibly related to crustal re-adjustment after the movement of deep-seated materials associated with the eruption. Re-adjustments of the crust after an eruption are not unusual. Measurements of changes of level after the eruption of Sakura-zima and Komagatake volcanoes in Japan revealed elliptical zones of depression. At Sakura-zima the area fell by as much as 2 metres near the volcano and by several centimetres 100 kilometers away (Minakami, 1936). Careful investigations of ground-surface displacements at Hawaii led Jones (1935) to the conclusion that " movement in and about the crater sometimes resembles that of a mosaic of blocks ". Minakami (1938) found evidence to support the theory of independently moving blocks in an area at Asama volcano which moved in a given direction irrespective of the cause of tilt. If Lamington volcano consists of a mosaic of blocks and was subjected to a post-eruption re-adjustment similar to that which occurred at Sakura-zima, then during the process of re-adjustment one of the blocks could presumably have behaved in the manner indicated by the extraordinary tilt.

LUNI-SOLAR INFLUENCES.

The gravitational pull of the sun and moon seem to have had a triggering effect on the activity of Lamington, particularly during the early highly explosive phase. The nature of the response suggests that both the magnitude and the direction of the tidal force are important in this effect.

Most of the large explosions occurred around the spring-tide periods of full and new moon (fig. 154). The outbursts of 21st January, 6th February, and 5th March occurred within a day or two of the maximum equilibrium tides when the tractive forces of the sun and moon are in either opposition or conjunction. The three explosions of 18th, 22nd, and 24th February were grouped about the time of the full moon of 21st February. This luni-solar maximum was unusually high for Lamington; the sun was close to the zenith position for the latitude of the volcano and the moon close to the zenith position for the corresponding latitude on the other side of the equator. The declination of the moon actually reached 9° north on 22nd February.*

Explosive activity represents only one aspect of the total activity of the volcano; much energy is also released in extrusive and seismic activity. If these additional manifestations are taken into account then it is found that some of the most important volcanic events take place close to periods of maximum lunar declination. The peak activity of the preliminary earthquake swarms seems to have coincided with a lunar declination maximum on 20th January (fig. 14). The climactic eruption occurred the next day. The next maximum on 3rd February introduced the phenomenal growth of 100 feet a day in the lava dome. The great rise in seismic activity and the explosion of 18th February occurred at a time of high lunar declination, and the next two swings in the lunar orbit had seismic oscillations to correspond with them (fig. 154).

CONCLUSIONS.

Mount Lamington belongs to a category of relatively acid volcanoes which have a characteristically discontinuous pattern of activity. Long periods of dormancy have led to periodic paroxysmal eruptions. These have consisted of a discontinuous series of outbursts ending with effusion of viscous lava whose physical condition has been such that the formation of lava domes has been more common than that of lava flows. This repetitive formation of domes gives doubtful support to the thesis that these protrusions are a stage in the development of the volcano. It is probably not without significance that the explosive activity associated with these protrusions has been Peléan in character. In short, dome formation and Peléan eruptions seem to be an established mode of activity of the volcano.

Paradoxically, it seems that the recent eruption owes its great devastating power to a lack of intensity. Had the eruptive mechanism possessed the power to throw all its ejecta high into the air there would have been a relatively harmless fall of cold ejecta over the surrounding country. Some of the explosions of this eruption did

* Later in the year, on 15th October, similar luni-solar dispositions preceded renewed extrusive activity from the eastern side of the dome.

in fact behave in this way. For the most part, however, power was lacking and a great proportion of the material was discharged in such a way that little atmospheric cooling was possible. With this retention of heat, gas continued to be released from the lava, thus providing a lubricant which allowed the masses of fragmental lava to descend as swift and sometimes devastating avalanches of the nuée ardente type.

The nuées ardentes ranged in intensity from the highly gas charged " ash hurricane " avalanches which were not strictly controlled by topography through the ponderous " block-ash flows " which moved down the radial valleys, to the almost gas-free avalanches descending from the flanks of the dome. The eruption produced no evidence of a directed explosion.

Verhoogen (1951) in his stimulating analysis of the mechanics of ash formation suggests that the type of explosion is governed essentially by the residual pressure in the lava vesicles at the moment of disruption:

" Let us now consider what happens when vesiculation begins. If a few bubbles form and rise swiftly by buoyancy to the surface the lava will 'boil' as it does in lava lakes. If, on the contrary, a large number of bubbles expand more rapidly than they rise, a time may come when neighbouring bubbles begin to coalesce. When such coalescence becomes general the lava will be fragmented into small shreds of liquid or glass between adjacent bubbles and may lose its cohesion. If, in addition, the pressure in the bubbles is still large at this time, the fragments will be blown apart, producing an explosion the intensity of which will depend essentially on the magnitude of this residual pressure. If it is small, we might observe a mild motion of a slowly expanding dust cloud ('sand flow' type); if the pressure is large a violent outburst of Vulcanian or Plinian type might occur."

The eruptive behaviour of Lamington appears to conform well with this conception. It is to be expected that, with the many factors influencing vesiculation rates in the heterogeneous environment of a volcanic conduit, activity will not be confined to one type. Mixed activity is more likely to be the normal state, as it was at Lamington. Special attention has been drawn to the close association between Vulcanian and Peléan explosions, both here and at other volcanoes which have produced nuées ardentes. The paroxysmal outbursts were more usually " mixed " although instances of " pure " types did occur. It is of interest to note that where velocities were measured during the post-climactic period rates of vertical translation (for the vulcanian explosions) were low. This fact, in combination with the typical absence of sounds, suggests that pressures even for the vulcanian outbursts were characteristically low.

Regarding the future of Lamington much reassurance can be derived from the fact that the deposits suggest long periods of dormancy as characteristic of its former activity pattern and from its close conformity with type; but such generalizations need qualification. In assessing the future of Mount Pelée, Perret (1937) made the following observations:—

" Three factors combine in the production of volcanic eruptions: accumulation, resistance and time: the principal of these is time; the other two factors are dependent upon it." In many ways the Lamington eruption seems a vindication of Perret's concepts: a long dormant volcano has had time to accumulate a vast store of energy which it releases with catastrophic violence, and time indeed seems to be the governing factor in the magnitude of the outburst. Further, the whole pattern of the eruptive cycle conforms beautifully with Perret's observations on the mode of activity for closed-conduit volcanoes.

An early phase of violent explosive activity was followed by overlapping phases of moderate explosive and effusive activity, and finally, in the process of gradually returning to the dormant state, the volcano lapsed into quiet effusion. Perret believed this pattern to be due to a zoning of the lava column which took place during dormancy. With the passage of time the more gas-charged elements of the magma rose gradually and occupied positions in the upper part of the conduit, leaving an inert magma at depth. Hence the closed conduit eruptive cycle with a violent initial phase and quiet end. Macgregor in his study of the petrology of Montserrat has found evidence to suggest that the zoning of the lava column in such volcanoes may be actually reversed, and some support to this view is given by the distribution of the green-hornblende-bearing magma of the present eruption. Further petrological work should shed additional light on this concept. In any event, whichever hypothesis is accepted, it should not affect the time-magnitude relationship of an eruption.

The length of the repose period as a measure of the probable behaviour of a volcano is an idea which should be regarded cautiously. In some instances a more potent factor governing the nature of an eruption may be the prevailing conditions of regional stress. Evidence has been presented to suggest that external factors, namely lunar-solar tractive forces and crustal stress conditions, can influence eruptive behaviour. Here it seemed that these external forces acted merely as a triggering mechanism on a closed system of volcanic forces which had reached a critical state of equilibrium. In the New Hebrides, where more active tectonic conditions prevail, time was an unimportant factor in the eruption of Ambrym volcano in 1950-1951. It seemed in fact that the volcanic system was open to the dynamics of regional stress conditions; the extraordinary magnitude and duration of the eruption seemed a direct response to the stress conditions which precipitated about the same time an unusually large number of earthquakes throughout the region.

Attention is drawn to the fact that the almost simultaneous eruption of Mount Pelée and the Soufrière of Saint Vincent in 1902 occurred during a period of abnormal seismic activity of the tectonic type. Some of the great earthquakes of the period 1897-1903 were located in, or adjacent to, the Caribbean region, and Gutenberg (1956) observed that the average annual energy released in shallow shocks throughout the world between 1896 and 1906 was about three times that for subsequent years. It is further suggested that the great volcanic disasters in the south-western region of the Pacific which ranged from Java to New Zealand in the 1880's were associated with a similar condition of abnormal crustal stress. In the light of these observations it is considered that the time factor in assessing volcanic conditions should be regarded with reservations.

Therefore, although there is good evidence to suggest that Mount Lamington will now return into a dormancy of a more or less protracted length it is possible that unusual tectonic movement could upset the normal pattern of events. Thus it is necessary to watch closely the regional seismic disturbances of the future. At the moment attention is focussed on the unusually large number of shocks occurring around the D'Entrecasteaux Islands and the possibility of reactivation of old volcanic centres in that area.

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APPENDIX I.

REPORTS ON THE BENDING OF THE HIGATURU FLAGPOLE.

The deformed flagpole shown in fig. 151 was bent by the nuée ardente of 21st January 1951. Its situation on the south-western, " upstream " side of Higaturu gave support to the assumption that the deformation had been produced by the nuée itself rather than by flying debris. Therefore, it was considered that an investigation of the physical properties of the pole should yield an upper limit for the velocity of the nuée ardente.

At the suggestion of Mr. H. Hume, formerly manager of the Newcastle Chemical Company, the problem was discussed with the Company's Works Engineer, Mr. R. Dunning, who agreed to undertake the investigation. His report and acknowledgments are appended.

REPORT ON INVESTIGATION OF WIND VELOCITY CAUSING DEFORMATION OF FLAGPOLE AT HIGATURU.

by R. DUNNING.

INTRODUCTION AND ACKNOWLEDGMENTS.

The problem was first referred by the writer of this section of the report, on behalf of Mr. G. A. Taylor, to Dr. J. N. Hool of the New South Wales University of Technology, who made the calculations appended hereto and arrived at the tentative conclusion contained therein, in the light of the information available at the time. This did not include any data on the properties of the material of the flagpole.

Subsequently, when sections of the flagpole were available, Mr. A. K. Johnstone of Newcastle College of the New South Wales University of Technology kindly undertook to investigate the problem further and an interview was arranged between him and Mr. Taylor, at which time a general picture of the circumstances of the volcanic blast was obtained.

Mr. Johnstone's separate report on the estimate of the velocity necessary to produce the deformation is based on observations of the pipe sections and on the moments of resistance of the pipe sections derived as described below.

The personal assistance given by Mr. J. Porteous of Stewarts and Lloyds (Aust.) Pty. Ltd. both in obtaining physical test data and in suggesting the method of determining that considerable solid particles were present in the air stream which struck the pole is acknowledged with thanks, as is the assistance of the management of Stewarts and Lloyds (Aust.) Pty. Ltd. and that of the Newcastle Chemical Co. Pty. Ltd. in making available facilities for carrying out the tests.

The writer is also indebted to Mr. Laurie Bogan of B.H.P. Research Department for his metallographic report which shows that the pitting on the surface of the pole facing the centre of the blast was caused by the impact of solid particles.

DETERMINATION OF MOMENTS OF RESISTANCE OF PIPE SECTIONS.

Although portions of the two upper parts of the pole were available for bend tests on the whole section, the portion of the lower 3-in. nominal bore pipe was rather too short to test in this manner and was, in any case, too large for the temporary test rig constructed. It was therefore necessary to obtain a method of calculating the moment of resistance of this section of the pole.

The method used to carry out the cantilever bend tests was to fix the one end of the test specimen to a rigid support by welding to the support two heavy plates with machined holes to take the specimen and inserting an extension arm consisting of a long solid plug and a pipe of similar section to the specimen in the other end. To this was attached a spring balance whose readings were checked against standard weights and which supported a container to which water could be added. The deflection for each load was read from a scale and the length of the radius arm measured.

Values of the angular deflection were calculated in each case and plotted on the accompanying graph. The value of the moment of resistance of the 2½-in. nominal bore pipe was obtained from the graph for the 4° bend, measured in the specimen at the bottom of this portion of the pipe. For the 2-in. nominal bore pipe it was necessary to extrapolate as a 30° bend could not be introduced on the test rig. However, at the end of the test the pipe had, for all practical purposes, become plastic, there being only some return from the deflected position with the load removed due, presumably, to strain hardening.

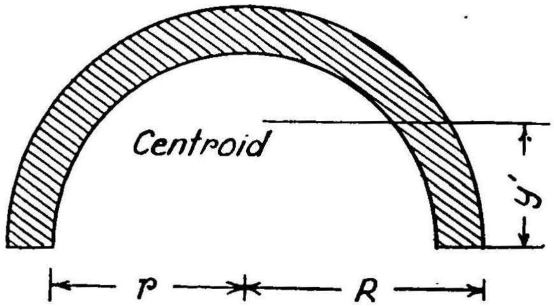
The moment of resistance of the 3-in. pipe was obtained by the following considerations.

Some difficulty is encountered in applying the conventional method of the plastic design theory when an exact, as distinct from merely safe design, result is required, because:—

(a) The assumption of rectangular stress distribution corresponding to the triangular distribution in elastic design theory is only an approximation.
(b) There is some strain hardening during deformation.
(c) The pipe changes section slightly during bending.

It is noted that in the theory of plastic design a flexural member becomes plastic when an appreciable zone of the member reaches the yield point. It would seem, therefore, that it is usual to take the yield stresses as the criterion, although it is evident that in order for the fibres nearer the centre to reach the yield point, the outer fibres must be extended to such a point that the stresses lie somewhere between the yield stress and the ultimate without reaching the ultimate, where it would seem that the member was at the point of failure. There can be no doubt that the pipes tested were nowhere near failing (that is, fracturing).

The following calculations show the moment of resistance obtained for the two extremes, taking first the yield stress and then the ultimate stress in tension as the applicable stress. The stresses in each case were obtained from test pieces cut from the specimens:—



$$\text{Area } A = 1.5708\,(R^2 - r^2)$$

$$y^1 = 0.424\,\frac{(R^3 - r^3)}{R^2 - r^2}$$

then Moment of Resistance $= f \times 2y^1 \times A$

where $f =$ applicable stress

then $MR = f \times 2 \times 1.5708 (R^2-r^2) \times 0.424 \dfrac{(R^3-r^3)}{R^2-r^2}$

$= f \times 1.335 (R^3-r^3)$

For 2″ Nominal Bore Pipe this gives $MR = 1.335 (1.206^3-1.046^3) \times f$

$= 1.335 \times 0.618 \times f$

$= 0.822 \text{ f}$

If f is taken as ultimate stress this gives $MR = 0.822 \times 23.2$

= 19 tons inches

= 42,600 lb. inches

If f is taken as yield stress this gives $MR = 0.822 \times 14.75$

= 12.1 tons inches

= 27,150 lb. inches

For 2½″ Nominal Bore Pipe this gives $MR = 1.335 (1.508^3-1.320^3) \text{ f}$

$= 1.335 \times (1.12) \text{ f}$

$= 1.49 \text{ f}$

Taking f as ultimate stress $MR = 1.49 \times 25.25$

= 37.6 tons inches

= 84,250 lb. inches

Taking f as yield stress $MR = 1.49 \times 15.85$

= 23.6 tons inches

= 52,800 lb. inches

For 3″ Nominal Bore—

D = 3.828

Wall thickness = 0.210

R = 1.764

r = 1.554

then $MR = 1.335 (1.764^3-1.554^3) \text{ f}$

$= 1.335 \times 1.74 \text{ f}$

$= 2.31 \text{ f}$

Taking f as ultimate stress $MR = 2.31 \times 23.2$

= 53.6 tons inches

= 120,500 lb. inches

Taking f as yield stress $MR = 2.31 \times 14.10$

= 32.6 tons inches

= 73,000 lb. inches

It will be noted that the values of the Moments of Resistance calculated using the yield stress correspond quite well to the actual results obtained in the cantilever bend tests. Thus, for the purpose of calculating the bending moment in the 3″ pipe at the base of the pole there can be no question, in view of the similarity of the sections, of the validity of accepting the yield stress as the actual stress, so that the value 73,000 lb. inches is taken for this section. From another approach it might be argued that whilst the theoretical average stress is somewhere between the yield and ultimate tensile stresses, the total result of factors (a), (b), and (c) above is to reduce this stress by coincidence to the numerical value of the yield stress.

SUMMARY OF RESULTS.

The Moments of Resistance on which the calculation of the wind velocity is to be based are as follows for the various sections of pipe.

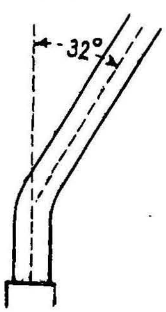
(i) 3″ Nominal bore pipe with a permanent set of 60°—73,000 lb. inches approx.

(ii) $2\frac{1}{2}$″ Nominal bore pipe with a permanent set of 45°—40,000 „ „ „

(iii) 2″ Nominal bore pipe with a permanent set of 30°—27,000 „ „ „

CALCULATION OF WIND VELOCITY *by* J. N. HOOL.

Assume in first instance that top pipe (8″ circ.) bent first.



Bending moment at point A with uniformly distributed load on top pipe.

$= \frac{1}{2}\, w\, l^2$ where w = load/unit length

l = length

$= f \times$ modulus of section

where f = yield stress of material

= say 28 tons/sq. in.

Circumference of 8″ gives outside diameter of 2.54″ (nearest water pipe size is 2″ pipe with O.D. of $2\frac{3}{8}$″ and wall thickness of gauge).

Modulus of section of this pipe is 0.623 in.^{3}.

$$\frac{1}{2}\, wl^2 = f \times \text{modulus of section}$$

$$\frac{w \times (17 \times 12)^2}{2} = 28 \times 2240 \times 0.623.$$

$$w = \frac{28 \times 2240 \times 0.623 \times 2}{417 \times 10^2}$$

$$= 1.87 \text{ lb./in.}$$

Fig 156

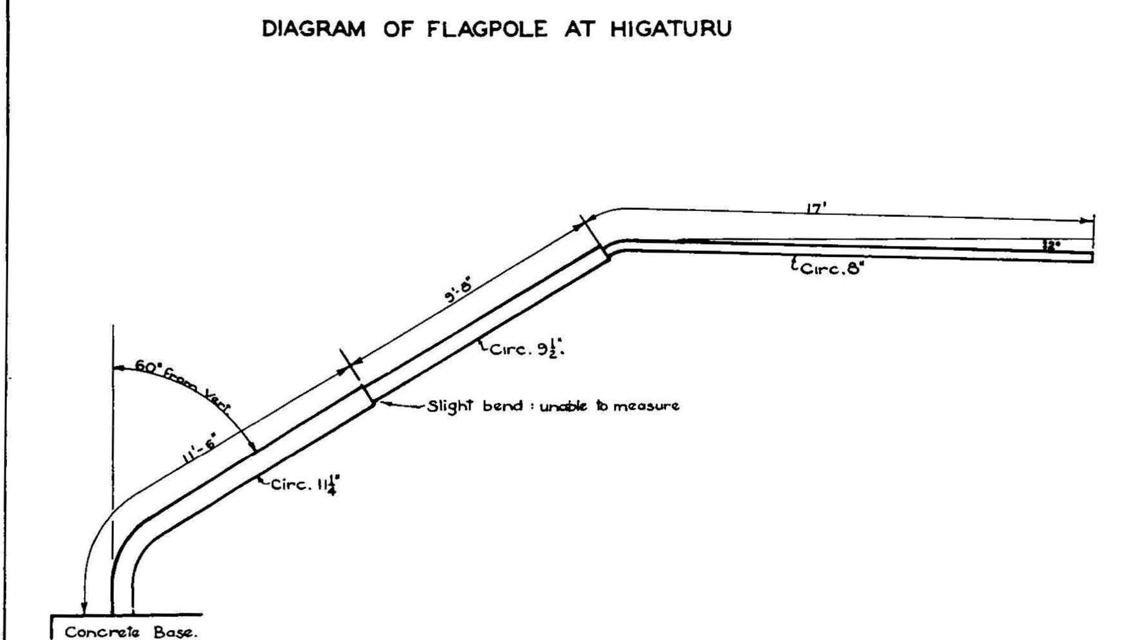
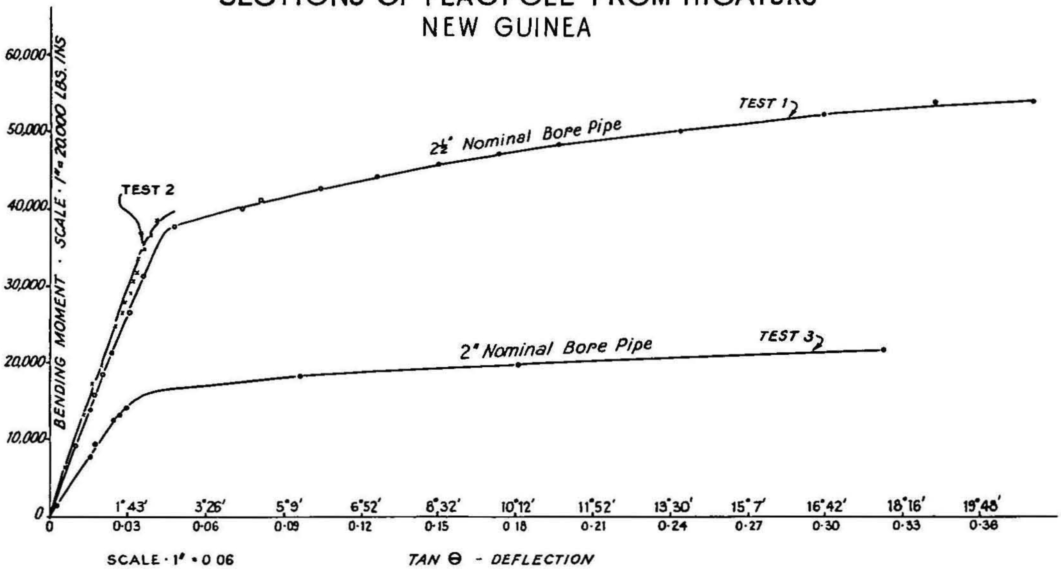


DIAGRAM OF FLAGPOLE AT HIGATURU
17'
12°
Circ. 8"
9'-8"
Circ. 9½".
60° from Vert.
Slight bend : unable to measure
11'-6"
Circ. 11¼"
Concrete Base.

Fig 157.

GRAPH OF BENDING MOMENT - DEFLECTION
SECTIONS OF FLAGPOLE FROM HIGATURU
NEW GUINEA



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Drag coefft. $C_D = \dfrac{D}{\frac{1}{2}\rho V^2 A}$

$D = \frac{1}{2}\rho V^2 A C_D$

where D = drag
ρ = density
V = air velocity
A = cross section area

Using graph of C_D against Reynolds number N_R for a cylinder placed at right angles to the flow, it is necessary to solve by trial and error method.

Try $C_D = 1.2$

$$V^2 = \frac{D}{\frac{1}{2}\rho A \times 1.2}$$

$$(PV = RT$$

$$\frac{1}{V} = \frac{P}{RT}$$

$$= 0.0709$$

For $T = 100°$ F.

and $P = 14.2$psi

$$\rho = \frac{1}{V \times g}$$

$$= 0.00221)$$

$$V^2 = \frac{1.87 \times 12}{\frac{1}{2} \times 0.00221 \times \frac{2.375}{12} \times 1 \times 1.2}$$

$$= 85600$$

$$V = 293 \text{ ft./sec.}$$

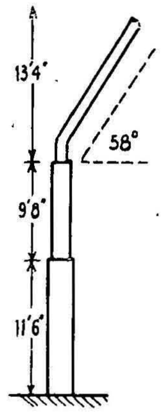
Checking, $N_R = \dfrac{V \times d}{\gamma} = \dfrac{293 \times 2.375/12}{1.82 \times 10^4}$

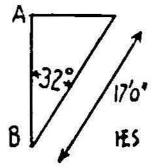
$= 3.19 \times 10^5$ — little high.

Try $C_D = 1.0$
$V^2 = 102800$
$V = 321$ ft./sec.

giving $N_R = 3.50 \times 10^5$ — near enough.

As top pipe is bent below the horizontal, it appears that the top pipe bent first. Before the bottom pipe bent, the configuration is as below.





$$AB = 17'0'' \times \cos 32^\circ$$
$$= 13.4$$

Assume 3″ water pipe for bottom section and 2½″ water pipe for middle section.

The wind speed closer to the ground will be less than that at the top of flag pole due to friction on the ground, shrubs, trees, &c. If a constant wind velocity for the full length of flag pole is assumed, the value obtained will be less than the value of the wind speed on the top of the pole only.

Bending moment at base $= f \times$ modulus of section.

$= 28 \times 1.82 \times 2240$ lb. inches.

$= 114000$ lb. inches.

Also bending moment

$$= \text{drag on bottom pipe} \times \frac{(11.5 \times 12)^2}{2} + \text{drag on middle pipe} \times 9.67 \times 12 \times (11.5 + 4.83) \times 12 + \text{drag on top pipe} \times 13.4 \times 12 \times (11.5 + 9.67 + 6.7) \times 12$$

$$= \tfrac{1}{2}\rho V^2 C_D \left\{ \left\{\frac{3.5}{12} \times \frac{1}{12}\right\} \frac{(11.5 \times 12)^2}{2} + \left\{\frac{3.0}{12} \times \frac{1}{12}\right\} \times 9.67 \times 12 \times 16.33 \times 12 + \left\{\frac{2.375}{12} \times \frac{1}{12}\right\} \times 13.4 \times 12 \times 27.87 \times 12 \right\}$$

$$= \tfrac{1}{2}\rho V^2 C_D (231 + 474 + 886)$$
$$= \tfrac{1}{2} \times 0.00221 \times V \times 1.1 \times 1591$$

$$V^2 = \frac{114000 \times 2}{0.00221 \times 1.1 \times 1591}$$
$$= 58900$$
$$V = 242 \text{ ft./sec.}$$

Checking $N_R = \frac{V \times d}{\nu} \quad \frac{242 \times 3.0/12}{1.82 \times 10^{-4}}$

$= 3.35 \times 10^5$ — little high.

Try $C_D = 1.0$

$V^2 = 64800$

$V = 254$ ft./sec.

giving $N_R = 3.50$ near enough.

If it can be assumed that the flag pole was bent by wind pressure only (no tree branches struck the pole) and that the pipe was standard water in good condition (not old boiler tube or refrigerator tube) then the minimum air speed is about 321 ft./sec. or 219 miles/hr.

As the top of the mast has been bent through approx. 32° only it is thought that the wind speed did not greatly exceed this figure.

(Sgd.) J. N. Hool.

Flagpole—Mount Lamington Eruption.

by L. B. BOGAN.

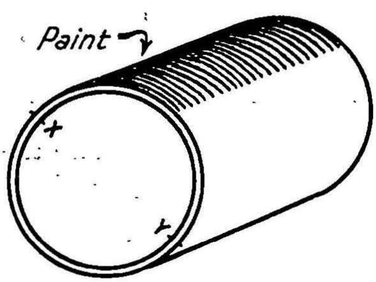
Specimens of a composite steel flagpole were received from Mr. Ray Dunning in an endeavour to supply certain evidence on the details of the collapse of the pole during the blast.

Pieces of the 3½", 3.0" and 2½" O.D. pipe sections were supplied. These all contained paint over a semi-circumference, it being argued that these areas were in the shadow from the blast. It was hoped that the bared section of the pipe would contain evidence of surface damage, indicating that the paint had been stripped off by a shot-blasting action from flying earth materials.

It was understood that the flagpole had been exposed for at least six months after the eruption to conditions which would certainly favour atmospheric corrosion. As a "shot blasted" surface could be expected to rust more quickly than a surface free from cold work, it might be anticipated that only the heaviest damage from flying debris would remain.

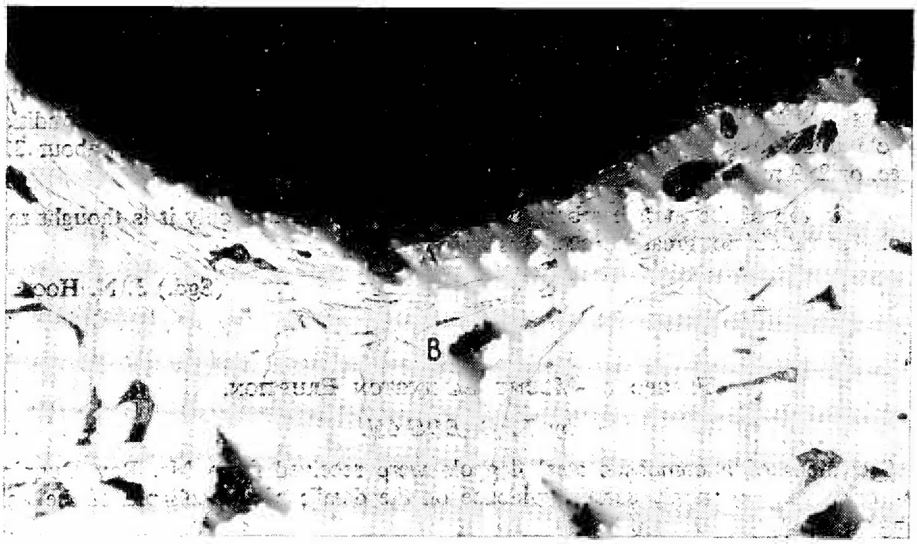
At any rate the following technique was adopted. Rings were cut from the pipe sections, the paint removed and the condition of the bared and covered portions of the metal circumference examined under a binocular microscope. The only difference in texture was that the surface exposed to the blast apppeared a little rougher.

Microscopic examination of metal was made at the ends of the one diameter bisecting the covered and uncovered areas as in the sketch below at X and Y.



Areas were found on the "blast" side of the tubes where there was severe cold work, at the bottom of the larger pits. Illustration of it is given in the Figure 153, below, which depicts the bottom of a pit with corrosion product dark and the steel structure light.

Cold work is marked between A and B in which several globules of corrosion product are in evidence.



None of this was observed beneath the paint layer on the various tubes.

Damage of the nature illustrated could well have been the result of the impact of pebbles or gravel against the steel at considerable velocity. Metallographic evidence of the shot blasting by small particles such as sand grains would have long ago been removed by atmospheric corrosion.

Comments on the Bending of the Higaturu Flagpole Caused by Mount Lamington Blast.

By A. K. Johnston.

1. The Pole must have been bent at point A first. There appears to be no other reasonable explanation of how it reached its final shape.
2. The above fact is significant, because all the figures, both theoretical and experimental, for the strength of the pipe show that any steady loading, even if it were on the top section alone, would cause the pole to bend at C first.
3. This indicates that the blast must have been stratified, so that it hit the top section first with sufficient suddenness to cause bending at A, while the inertia of the lower sections prevented immediate bending at C. The blast following on then reached the lower sections and caused the bending at C.
4. Previous theoretical calculations overlook the above facts. Furthermore the drag coefficients used were those corresponding to steady flow, which the blast certainly was not. This causes the previous theoretical estimates of velocity to be too high, even assuming that the blast was pure air.

5. It is almost certain, however, that the blast was not pure air. The samples cut from the pipe have a shot-peened appearance on the upstream side as though they had been hit by a shower of solid particles. All the paint is removed from the half-circle of the upstream side but is intact on the down-stream side. This would not be so if it were simply a case of exposure to sun and weather.
6. The velocity of a concentrated shower of solid particles necessary to bend the pole is obviously less than that for pure air to bend it. How much less depends on the density, etc., of particles, which is unknown. However, the appearance of the pipe surface indicates that the density of particles must have been considerable.
7. The term " blast velocity " needs defining. Obviously there is no steady velocity in this case. " Blast velocity " is therefore taken to mean the highest instantaneous velocity of gas or solid particles which impinged on the pole.

Summing up then, we may say that the blast was stratified when it reached the pole, hitting the top portion first. The previously estimated " blast velocity " of 200 m.p.h. should be reduced on two accounts—first because the phenomenon is unsteady and the steady flow drag co-efficients are too small, secondly because it appears that solid material of much higher density than air is involved. The velocity is then considerably less than 200 m.p.h. and may be no more than 100 m.p.h.

APPENDIX II.

PETROLOGICAL EXAMINATION OF MOUNT LAMINGTON VOLCANIC ROCKS.

By J. Kerry Lovering.

The Mount Lamington volcanic rocks were collected by Mr. G. A. Taylor, after the eruption of the volcano in January, 1951. The extrusive rocks are composed of six main types of andesite.

OLDER LAVAS.

Three types of andesite are found in the three remaining walls of the old crater.

South Wall: green-hornblende andesite.

The lavas of the south wall may be the oldest in the vicinity. Mr. S. J. Paterson, lately of C.S.I.R.O. Land Research and Regional Survey Section, states (unpublished report): "The oldest lava flows lie in the south-eastern slopes. They are strongly dissected ".

The rock consists of porphyritic phenocrysts between 1 and 2 mm. in diameter, in a grey groundmass which makes up 45 per cent. of the rock, and consists of a large devitrified mass of inter-locking microlites of feldspar, some of albitic composition, and gypsum, with chlorite veins and disseminated particles of iron oxide. Zoned andesine phenocrysts of composition An48 to An38 make up 33 per cent. of the rock. The optic angle ranged from (+) 85° to (—) 88°. Oscillatory zoning is common. Most grains are twinned on complex albite-carlsbad twinning laws; carlsbad and albite twins are also found. Many grains are cracked, and some have resorbed margins. Inclusions are seen in many zones.

Grains of pleochroic green hornblende (11 per cent.) generally have alteration rims of fine particles of magnetite and chlorite. The hornblende is altered to green actinolite, biotite, and colourless chlorite. Green-brown biotite grains (3 per cent.) are mostly unaltered, but many grains have rims of granular magnetite. The biotite is pleochroic from green to pale yellow.

Euhedral and anhedral grains of magnetite (5 per cent.) are now partly replaced by hematite. Ragged grains of a diopsidic pyroxene form 2 per cent. of the rock. The accessory minerals include well-cleaved grains of anhydrite, euhedral grains of apatite, and pyrite.

In the analysis (No. 3, Table III.) of this andesite, the high percentage of sulphur trioxide can be explained by the large amount of gypsum in the groundmass.

Western Wall: pyroxene andesite.

The western wall of the crater is built up by flows from previous eruptions. The wall is banded, but the flows are very similar petrographically. The rock is light grey and contains phenocrysts of magnetite, pyroxene, feldspar, amphibole, olivine, and biotite, which in the hand-specimens show a slight layering arrangement in an aphanitic groundmass.

The groundmass forms 70 per cent. of the rock and consists of calcic feldspar microlites, iron oxide particles, and fine pyroxene grains in a microcrystalline and glassy matrix. The feldspar and pyroxene microlites have a sub-parallel arrangement, indicating flow movements.

Tabular grains of diopside, with Z $\triangle$ c = 37°, and pigeonite grains make up 7 per cent. of the rock. Pyroxene in the groundmass raises this percentage considerably. The diopsidic grains are cracked and many have rims of pigeonite. Feldspar grains up to 5 mm. long constitute 5 per cent. of the rock. The grains show oscillatory zoning; small cores of labradorite (An56) are surrounded by andesine zones ranging from An45 to An38, and some thin zones of labradorite (An64 to An56). The grains are twinned and generally very fractured, with altered and resorbed rims. Some zones contain glassy inclusions.

The euhedral amphibole is lamprobolite, which is distinguished by its pleochroism from dark-brown to yellow-brown and its nearly straight extinction. Some grains are zoned around cores of darker lamprobolite. Only 3 per cent. lamprobolite is now present in the rock, which originally contained at least 15 per cent. lamprobolite, most of which has been pseudomorphed by magnetite particles, some plagioclase, pyroxene, and occasional biotite. As the euhedral shape of the lamprobolite grains can be recognized, the alteration probably took place in situ.

The large percentage of pyroxene in this rock may have resulted as alteration of the lamprobolite as well as original pyroxene. Certainly some is seen to be pseudomorphing lamprobolite, and more may have formed in this way. However, if volatiles were not abundant during the eruption of this lava, much of the pyroxene may have formed originally (Larsen et al, 1937).

Magnetite (12 per cent.), consisting of euhedral and anhedral grains, is partly replaced by hematite; magnetite pseudomorphs lamprobolite and biotite. Biotite mica is often replaced by magnetite on the margins, and olivine grains are fractured and serpentinized in part.

The rock is a *pyroxene andesite*. The analysis (No. 4, Table III) shows that it is poorer in silica than the other andesites. The high calcium oxide is to be expected in a diopside-rich andesite.

One of the older flows on the western side is a *hyperesthene basaltic andesite*. A slide of this was lent to me by Mr. S. J. Paterson.

The thin section reveals a porphyritic merocrystalline rock. The groundmass, constituting 50 per cent. of the rock, consists of feldspar microlites and iron oxide particles in a greenish glass.

Twinned and zoned phenocrysts of feldspar (41 per cent.) range in composition from a basic labradorite, An66, to an inner core of a basic bytownite, An84. Oscillatory zones of An67 and An84 surround the inner core. The feldspars are cracked and hematite fills the cracks. Hypersthene (5 per cent.) occurs as euhedral grains, a few of which are cracked and filled with hematite. Diopside makes up 3 per cent. of the rock and magnetite (1 per cent.) occurs in irregular grains.

East Wall: magnetite-lamprobolite andesite.

The eastern wall resembles a plug which has been considerably shattered. There is a denser inner core with a more glassy outer shell. These eastern wall andesites are characterized by the large amount of magnetite, which replaces the amphibole and biotite.

The inner core is a medium-grained rock. Medium-grained phenocrysts, 4 mm. to 0.1 mm. in size, are so arranged as to suggest a slight fluidal banding. They lie in an aphanitic groundmass of microcrystalline material with disseminated iron particles and some interstitial glass. This groundmass constitutes 45 per cent. of the rock.

Feldspar phenocrysts (37 per cent.) are composed for the most part of andesine of composition An42 to An32. Oscillatory zoning of andesine and a few thin zones of labradorite surround cores of bytownite (An80). The grains are twinned and fractured. They are mostly euhedral, but may have resorbed margins. Zones of isotropic inclusions are present. The amphibole, lamprobolite (8 per cent.), has been extensively altered to magnetite with some fine granular pigeonite and plagioclase. The lamprobolite is highly pleochroic from brownish-red and greenish-yellow and has straight extinction.

Magnetite also replaces biotite, so that only 2 per cent. of brown biotite is present as phenocrysts in the rock. Magnetite (8 per cent.), has idiomorphic outlines of both amphibole and biotite; it also occurs in anhedral and euhedral grains which are mostly replaced by hematite. Accessory minerals are olivine, diopside, and apatite.

The outer shell type is a medium-grained merocrystalline rock, which is light-coloured, with a slightly blotchy appearance.

The phenocrysts occur in a grey aphanitic groundmass, which constitutes 60 per cent. of the rock, and consists of andesine microlites which have a sub-parallel arrangement, iron oxide globules, and small pyroxene grains, in a glassy and microcrystalline matrix.

Feldspar phenocrysts (25 per cent.), show oscillatory zoning of labradorite and andesine (An42 to An37) around a core of bytownite. The ferromagnesian minerals are mainly replaced by magnetite, which also occurs as anhedral and euhedral grains, many of which are partly replaced by hematite.

Lamprobolite phenocrysts (3 per cent.) are greenish-brown with an extinction angle of 8°; the euhedral grains have been largely replaced by magnetite. Only 1 per cent. of red-brown biotite is present, after being replacd by magnetite.

Fractured grains of olivine (2 per cent.) and anhedral grains of pyroxene (2 per cent.), both augite and pigeonite, and accessory apatite are present. Globules of colourless chlorite occur in the groundmass.

The analyses (Nos. 1 & 2, Table III) reveal high percentages of ferrous oxide, magnesium oxide, and calcium oxide.

NEW LAVAS

The three main types of lava extruded in the recent eruption are temperature variants of the same magma. Type I is the rarer high temperature variant, Type II, in the medium-high temperature range, is abundant, as is Type III in the low temperature range.

Anhydrite-bearing brown-lamprobolite andesite (Type II) is most prominent, and is found in all parts of the volcano, with some variation in colour. It is a grey aphanitic rock with medium-sized phenocrysts, which, in some specimens, give a distinct banding and fluidal arrangement.

Thin sections reveal phenocrysts in a groundmass constituting 53 per cent. of the rock. The groundmass consists of a microcrystalline feldspar, globules of colourless chlorite, and iron oxide particles. This microcrystalline material flows around phenocrysts of feldspar (28 per cent.), lamprobolite (9 per cent.), biotite (1 per cent.), magnetite (2 per cent.), and accessory minerals. The phenocrysts range from 6 to 0.5 mm. in size.

Oscillatory zones of andesine between An45 and An30, and labradorite An65, surround cores of labradorite which are often irregular in outline. The grains are twinned, and fractured; some have resorbed margins; many have zones of inclusions.

The euhedral amphibole is a lamprobolite which is not wholly oxidized. The extinction angle varies from 5° to 8° in various parts of the lava. The negative optic angle is 66°. The pleochroic scheme is as follows: X = yellow, Y = yellow-brown, Z = brown. Many grains are strongly zoned about a darker core which is more oxidized. In some grains the zoning is due to new growth about an older grain which has an alteration rim of magnetite and fine pigeonite. Some of the red-brown to yellow-green biotite grains (1 per cent.) are partly oxidized; the optic angle is, in some grains, as large as 16°.

Magnetite grains are irregular in shape and size. Small grains of pigeonite (2 per cent.) and augite (1 per cent.) are present. A little olivine occurs as fractured grains, and some are altered to augite. Around the olivine are clusters of small lamprobolite grains. Anhydrite occurs in small irregularly-shaped grains fringed with iron oxide particles, and is characteristic of the lava. Euhedral grains of apatite, an important accessory, are seen as inclusions in feldspar grains and as large phenocrysts.

Analyses of this lava include Nos. 10 and 12, Table III. These analyses are similar, and support the mineralogical information.

Anhydrite-bearing red-lamprobolite andesite (Type I) occurs extensively as a mealy segregation around the vents on the east dome. It also occurs between the monolithic blocks of the terminal spine. The rock is generally distinctive, both in section and in hand specimen. It is dark reddish-brown, and contains medium and large phenocrysts in an aphanitic groundmass.

Phenocrysts, with an average grainsize of 2 mm., are in a microcrystalline and glassy groundmass which makes up 50 per cent. of the rock. Feldspar phenocrysts (23 per cent.) are twinned and exhibit oscillatory zoning. Cores An51 to An48 are surrounded by zones ranging from An35 to An26 with occasional thin zones of labradorite (An65). Many outer zones contain inclusions of glass and anistropic material.

Euhedral grains of lamprobolite (19 per cent.) are characteristic of this lava. The pleochroic scheme is as follows: X = olive-yellow, Y = light brown, Z = red. The extinction angle is 0°. The lamprobolite grains are frequently twinned and zoned; some grains have a new growth around darker former grains which occasionally have alteration rims of magnetite and pyroxene granules. Many margins of grains are resorbed. Pigeonite (1 per cent.) occurs in small grains and clusters. Magnetite occurs as irregularly-shaped grains, and, together with fine pyroxene granules, as marginal alteration products of lamprobolite and red-brown biotite (2 per cent.). The biotite has been oxidized; some grains have optic angles up to 15°. Surrounded by clusters of lamprobolite and biotite grains are small olivine grains (1 per cent.), many of which are cracked and altered to pyroxene, serpentine minerals, and hematite. Euhedral apatite and fragments of anhydrite are accessory minerals.

Analysis No. 9, Table III, reveals a high alumina content and a high ferric oxide content.

Anhydrite-hornblende andesite (Type III), is a light grey rock which contains medium and fine phenocrysts in an aphanitic groundmass. Specimens of this rock were collected from the north face.

Feldspar phenocrysts (27 per cent.) are twinned and zoned extensively. Cores of labradorite (An65-60), are surrounded by oscillatory zones of andesine (An50 to An35), with a few thin zones of labradorite. Some zones have glass inclusions.

The hornblende phenocrysts (13 per cent.), with an extinction angle of 19°, have a pleochroic scheme: X = yellow-green, Y = green, Z = greenish-brown. Phenocrysts of green-brown biotite (45 per cent.), with a small 2V, grains of magnetite (2 per cent.), and the accessory minerals, euhedral apatite, olivine, and fragmental anhydrite, complete the list of minerals present. The groundmass (5 per cent. of the rock) consists of colourless glass containing fine microlites of feldspar and pyroxene, and microcrystalline material which appears to flow around the phenocrysts.

Analysis No. 11, Table III, shows that there is very little chemical difference from Type II.

Pumiceous material which was ejected at the first eruption, as bombs and ash flows, is similar in chemical and mineralogical composition to the anhydrite-hornblende andesite. Texturally, however, this light grey pumiceous material is different. In the groundmass are numerous glass shards which, with fine dust particles, indicate flow movements around the phenocrysts. Some of the ash which fell in the surrounding district also contains rock fragments derived from the Older Lavas.

One specimen collected from the north face is similar to older lavas from the west wall and is a xenolith in the new lava.

XENOLITHS.

Xenoliths occur in the new lavas, generally in Type II.

One of the xenoliths, No. 38D, in Type II is more in the nature of a segregation of part of the lava. Euhedral grains of feldspar, lamprobolite, biotite, olivine, magnetite and accessory apatite are set in a glassy groundmass which constitutes only about 25 per cent. of the rock. The glass contains some opaque dust particles and some crystallites which emphasize swirling flow movements in the rock. The feldspar consists of some andesine zones surrounding a core of partly resorbed calcic plagioclase. Around numerous olivine grains and magnetite grains are clustered grains of lamprobolite and biotite. The junction between the segregation and Type II is easily distinguished by the difference between the glassy groundmass of the segregation and the microcrystalline groundmass of Type II. Grains are aligned sub-parallel to the junction.

Hornblendite occurs as xenoliths in Type II. It is a black and white holocrystalline rock, which consists of brown-green hornblende with pleochroic scheme: X = green-fawn, Y = green-fawn, Z = brown. The negative optic angle is 53° and the extinction angle is 22°. Another amphibole, ferrotremolite, is also present. The feldspar present is labradorite of composition An64. Anhydrite occurs in large well-cleaved grains. It has a high birefringence and flat relief, and shows twinning and oblique extinction. Biotite is also present. Probable pyrrhotite occurs as irregular grains. Sphene is an accessory.

Analysis No. 17, Table III, gives the composition of the hornblendite, showing the low silica and soda, with a high alumina, iron, magnesium, lime, and sulphur trioxide content.

This hornblendite may be associated with another xenolith—a dunite of forsterite composition (analysis No. 18, Table III) which is veined with white enstatite, and rimmed with hornblende and biotite. The origin of these xenoliths is unknown, but serpentines occur in the vicinity of the volcano and the lava may have passed through the ultrabasic source of these serpentines.

Specimens from a dyke intruding some of the older lava are a fine-grained partly-metasomatized dolerite. Laths of andesine surround grains of epidote, augite, and magnetite, and green chlorite fills the space between these minerals. Much of the plagioclase is altered to chlorite and calcite, much of the pyroxene to tremolite, and some epidote to clay minerals.

DISCUSSION.

The examination of the older and new lavas of the Mt. Lamington volcanic rocks reveals a general similarity of type and texture, but some dissimilarities in mineral content. Both are fairly siliceous andesites. The new lavas are slightly more siliceous and have a higher soda content. All the lavas are porphyritic. Phenocrysts and groundmass are each about 50 per cent. of the rock. The groundmass of the older lavas is either devitrified, and consists of feldspar microlites, some albitic in composition, and iron oxide particles, or it consists of microcrystalline material with some interstitial glass. The new lavas have a cryptocrystalline groundmass with interstitial glassy material.

Feldspar.

Feldspar grains from the western and eastern walls have some cores of bytownite, surrounded by zones of basic andesine and labradorite. The feldspars of the new lavas are generally more sodic: zones of sodic andesine surround cores of labradorite.

Twinning of feldspars on complex albite-carlsbad, carlsbad, and albite twin laws is common to all lavas. Some primary twinning is present. Many of the polysynthetically twinned crystals are probably due to mechanical stresses caused by external factors, such as temperature and pressure changes within the magma. Emmons and Gates (1943) consider that polysynthetic twinning is due to mechanical stresses after the feldspar has crystallized. Although Donnay (1943) disagrees with this view, it seems satisfactory for feldspars from volcanic rocks. Many of the feldspar phenocrysts are extensively shattered. This may be due to more intense stresses operating during eruption.

Small crystals are quite commonly welded on to larger ones. Most of the features noted by Baker (1949), in the feldspars of Mt. Bagana andesites, are present in the feldspars of Mt. Lamington.

The resorbed margins of most feldspar phenocrysts suggests a chemical inequilibrium between the phenocrysts and the groundmass.

Normal oscillatory zoning is a very important feature in the feldspars of both new and older lavas. Cores of calcic plagioclase are surrounded by zones of andesine, labradorite, and more andesine in a rhythmic pattern. Hills (1936) has suggested that the core crystallizes in equilibrium with the liquid magma, and as crystallization proceeds by slow diffusion, zones of more feldspar will be deposited. The liquid beyond will correspondingly be more calcic. Slowing down of crystallization will allow diffusion of the lime into the liquid next to the crystal and a more calcic zone will be deposited. However, in some grains the cores are zoned from bytownite or labradorite to andesine, with added oscillatory zones ranging in composition from labradorite to andesine and appear to have a rounded and resorbed margin, which may be marked by a zone of inclusions. The outer zones, ranging from labradorite to andesine or even oligoclase, wrap around the inner zoned core. Perhaps the zoned core crystallized and was later partly resorbed and assimilated in magma with which it was not in equilibrium. Many amphiboles have darker cores with smaller extinction angles than the outer zone; assimilation of amphibole by later magma may also explain this fact.

Amphibole and Biotite.

Lamprobolite and red biotite occur in older lavas of the western and eastern walls. Both minerals are extensively altered to magnetite, with some pigeonite, biotite, and feldspar granules.

A brown lamprobolite (Type II), and a red lamprobolite (Type I) are found in the new lavas. The red lamprobolite occurs under special conditions around the vents and between the monolithic blocks. The biotites are also partly oxidized to red biotite in these special parts of the volcano; but they are not altered to magnetite.

Lamprobolite and the oxidized red biotite are formed as a result of oxidation. In an oxidizing environment above a temperature of 750° C. ferrous iron in green hornblende changes to ferric iron in lamprobolite (Barnes, 1930). Oxidation of biotite results in a change to red biotite (Winchell, 1951, p. 376). The formation of SO_2, SO_3

and H_2S involve exothermic reactions; the heat evolved might raise the temperature of the magma at the surface where the abundance of atmospheric oxygen could allow the oxidation of lamprobolite and biotite to proceed at these high temperatures. This may explain the presence of red lamprobolite and red biotite around the vents. Both Types I and II and the older lavas of the eastern and western walls must have reached at least 750° C.

Still higher temperatures result in the distintegration of lamprobolite and biotite to pseudomorphous aggregates of magnetite, pyroxene, and plagioclase, as seen in the older lavas of the western and eastern walls.

According to Wittels (1952) amphibole distintegrates into hematite, pyroxene, and plagioclase, with some olivine and magnetite, at very high temperatures. Other workers (Grigoriev and Isküll, 1937) have obtained magnetite, pyroxene, and water from amphiboles at very high temperatures.

Larsen, Irving, Gonyer, and Larsen (1937) describe similar features in the andesites of the San Juan Region, Colorado. There, phenocrysts of hornblende and biotite have been reconstituted and have resulted in pseudomorphous aggregates of iron ore, pyroxene and plagioclase. This process involves oxidation of ferrous iron and is favoured by near-surface conditions including high temperatures and loss of water from the magma. Most of the reconstitution took place after eruption of the lava, when (p. 894) " water and other gases escaped, and the hornblende and biotite were no longer in equilibrium with the mineralizer-poor liquid and were resorbed ". This explanation implies that slow cooling of the magma is necessary for resorption; however, high temperatures are required to remove the hydroxyl ion from the amphibole structure. The rate of cooling will certainly influence the crystallinity of the groundmass but will have no affect on the conversion of amphibole to magnetite, pyroxene, and feldspar unless high temperatures have been reached.

It is unlikely that very high temperatures would become very widespread at the surface (exothermic reactions involving volatiles could only be a local effect). For the disintegration of amphibole throughout the older lavas of the eastern and western walls of the crater, it is probable that high temperatures (or very likely high confining pressures) were attained just before eruption.

Green hornblende and green-brown biotite are found in the older lavas of the south wall. The temperatures of these lavas must have been below 750° C.; not subject to oxidizing processes.

As the amphiboles and biotites of the new lavas and the south wall lavas have not disintegrated to magnetite and associated products, it seems that the temperature of the new lavas and the south wall lavas was not as high as that of the eastern and western parts of the older lavas. The higher temperature in the western and eastern older lavas may have meant they were less viscous.

Anhydrite

Anhydrite, occurring as small fragments rimmed with magnetite particles, is found in small amounts in the lavas of the south wall, and it is characteristic of all the new lavas. It is unusual in a volcanic association and is not a primary mineral here. The fragments may be the result of the assimilation of material similar to the hornblendite xenolith, which contains primary anhydrite.

Olivine

The association of olivine grains with lamprobolite in the new and older lavas is interesting. The olivine grains are surrounded by a rim of small grains of lamprobolite, and biotite.

Pyroxene

The association of diopside or augite and pigeonite noted in the older lavas of the west and east, and Types I and II of the new lavas, is quite common according to Hess (1941). Pigeonite in the groundmass is found in rapidly cooled extrusives.

The hypersthene basaltic andesite, containing hypersthene and diopside, probably crystallized slowly.

CONCLUSION.

The Mt. Lamington volcanic rocks form a suite of six different types of andesite. The overall picture shows a gradual increase, with time, in the silica and soda content of the andesites. This increase is reflected in the trend towards a more sodic type of andesine. The oscillatory zoning of the feldspar is common in all the lavas. Mechanical factors have probably caused the extensive twinning and fracturing of the feldspars.

Alteration to magnetite, pyroxene, and plagioclase, of the amphiboles and biotites in the western and eastern walls of the older lavas indicates a very high temperature for these lavas.

The new lavas which contain lamprobolite and red biotite reached a lower temperature, perhaps associated with volatiles. The green hornblende of the south wall older lavas and the Type III of the new lavas indicates formation of these lavas in a non-oxidizing environment at a temperature less than 750° C.

Microscopic examination of these rocks has revealed chemical inequilibrium between phenocrysts (except pyroxene and olivine) and groundmass. Larsen *et alia* (1938, p. 429) considered that " many of the plagioclase and other phenocrysts of the lavas of the San Juan region did not crystallize from a magma of the composition of the rock in which we find them, but must have been derived from the partial assimilation of other rocks, or by the mixing of two magmas "; examination of the Lamington volcanics leads to similar conclusions. Assimilation of sialic rocks by basaltic magma probably explains the features of the Lamington volcanics.

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