COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

Record No. 1970 / 21

Ulawun Volcano, New Britain: Geology, Petrology, and Eruptive History Between 1915 and 1967

by

R.W. Johnson

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SUMMARY

Ulawun, or The Father, is an active stratovolcano, 2300m. high, on the north coast of New Britain. It is made up of basaltic lava flows and interbedded fragmental deposits, most of which were erupted from a central vent. Many of the lava flows show clastic textures caused by fragmentation of the lavas during flowage.

The symmetry of the volcano is broken by a prominent east-west escarpment, 160m. high, that straddles the southern flank of Ulawun. This escarpment is probably the remains of a caldera or linear graben formed by collapse of the summit area of the volcano.

A "younger cone" rises from the base of the east-west escarpment, and its products are conformable with those of the older part of the volcano on the western, northern, and eastern sides. In March, 1969, when the summit of the younger cone was visited, a crater, 130m. deep and 400m. wide, was present, but this was modified and buried by the products of volcanic activity in January, 1970.

The earliest observed eruptions of Ulawun took place in 1915 when explosive activity produced ash falls. Other notable periods of explosive activity were in 1960-62, 1963, and 1967. Volcanic activity in January, 1970, produced ash falls, nuées ardentes, and lava flows.

The Ulawun lavas contain phenocrysts of plagioclase, augite, olivine, hypersthene, and to a lesser extent pigeonite and iron-titanium oxide. The groundmass constituents are plagioclase, augite, pigeonite, iron-titanium oxide, interstitial glass and, in some rocks, hypersthene. Chemical analyses of four Ulawun rocks show them to be tholeiite basalts.

1. INTRODUCTION

Ulawun is an imposing active stratovolcano that rises from the north coast of New Britain to a height of 2,300m. above sea-level* (co-ordinates: 5°02'S; 151°21'E). It is the highest of a series of volcanoes between Willaumez Peninsula in the west, and Open Bay in the east (figure 1).

Ulawun, also known as The Father, is flanked to the southwest by Bamus volcano (South Son) and Galloseulo, and to the northeast by Likuranga (North Son). Twenty five kilometers to the northwest, across Expectation Strait, is the volcanic island of Lolobau. With the exception of Likuranga, all of these volcanic centres are active, and they are listed in the International Volcanological Association "Catalogue of the active volcanoes of the world" (Fisher, 1957). Ulawun is the most active of the four centres, and it has displayed notable periods of explosive activity in 1915, 1960-62, 1963, and 1967.

2. TOPOGRAPHY AND GENERAL GEOLOGY

At the 200m. contour level (figure 2), Ulawun has an area of about 200 sq. km., and maximum diameter of 18 km. in a northeast-southwest direction; it is 15 km. across from northwest to southeast. The outer slopes of the volcano increase uniformly from zero at sea-level to a maximum of 37° just below the summit crater.

The southern slopes are straddled by a prominent, north-facing east-west escarpment which is about 160m. high, and 1715m. above sea-level at its highest point (figures 2, 3, 4, and 5). Rain forest mantles the entire escarpment, including the steep northern face. Elsewhere on the volcano an unbroken forest canopy extends from sea-level to a sharply defined upper limit between 1000m. and 1450m., above which the scoria- and ash-covered slopes are more or less clear of vegetation.

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* This value is the metric conversion of 7,546', the altitude given on the United States Army 4" to 1 mile map of Central New Britain (1943). All other altitude values given in this report were read from a pocket altimeter, uncorrected for diurnal pressure variations.

There are two major stream valleys on the mountain. The Matisibu or Western Valley* trends west from the base of the east-west escarpment, and the Dulinidipedal or Northwestern Valley extends from the summit crater to the northwest, almost reaching the coast about 5 km. northeast of Ulamona Roman Catholic Mission Station and Sawill (figures 1 and 2). Both stream valleys cut deep sections through the western flanks of the volcano.

Ulawun consists of thin lava flows and interbedded scoria and ash of basaltic composition; dacitic and rhyolitic rocks appear to be absent. The basaltic lavas are dark aphanitic rocks with phenocrysts of plagioclase and pyroxene; in some, olivine phenocrysts are also visible in hand specimen.

The lava flows and pyroclastic material were erupted from a central vent whose position seems to have changed little throughout the history of the volcano. The prominent escarpment of the south flank of Ulawun suggests that there was large-scale collapse of the summit area. Later eruptions, however, appear to have continued from a central vent, producing a younger cone whose products are conformable with those of the older parts of the volcano on the western, northern, and eastern sides. Satellite cones and craters are present on the western and eastern flanks.

The first and only recorded ascent of Ulawun was made by N.H. Fisher and C.E. Stehn in August, 1937 (Fisher, 1937). From Ulamona Mission they ascended the Northwestern Valley, reaching the summit in two days and returning to Ulamona on the following day. Short accounts of the geology of Ulawun have been presented by Fisher (1937, 1939b, 1940, 1957), and records of the eruptive history of the volcano since 1950 are available in the unpublished Monthly Reports of the Rabaul Volcanological Observatory.

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* In this report the local valley names have been replaced by the simpler more convenient names "Western" and "Northwestern".

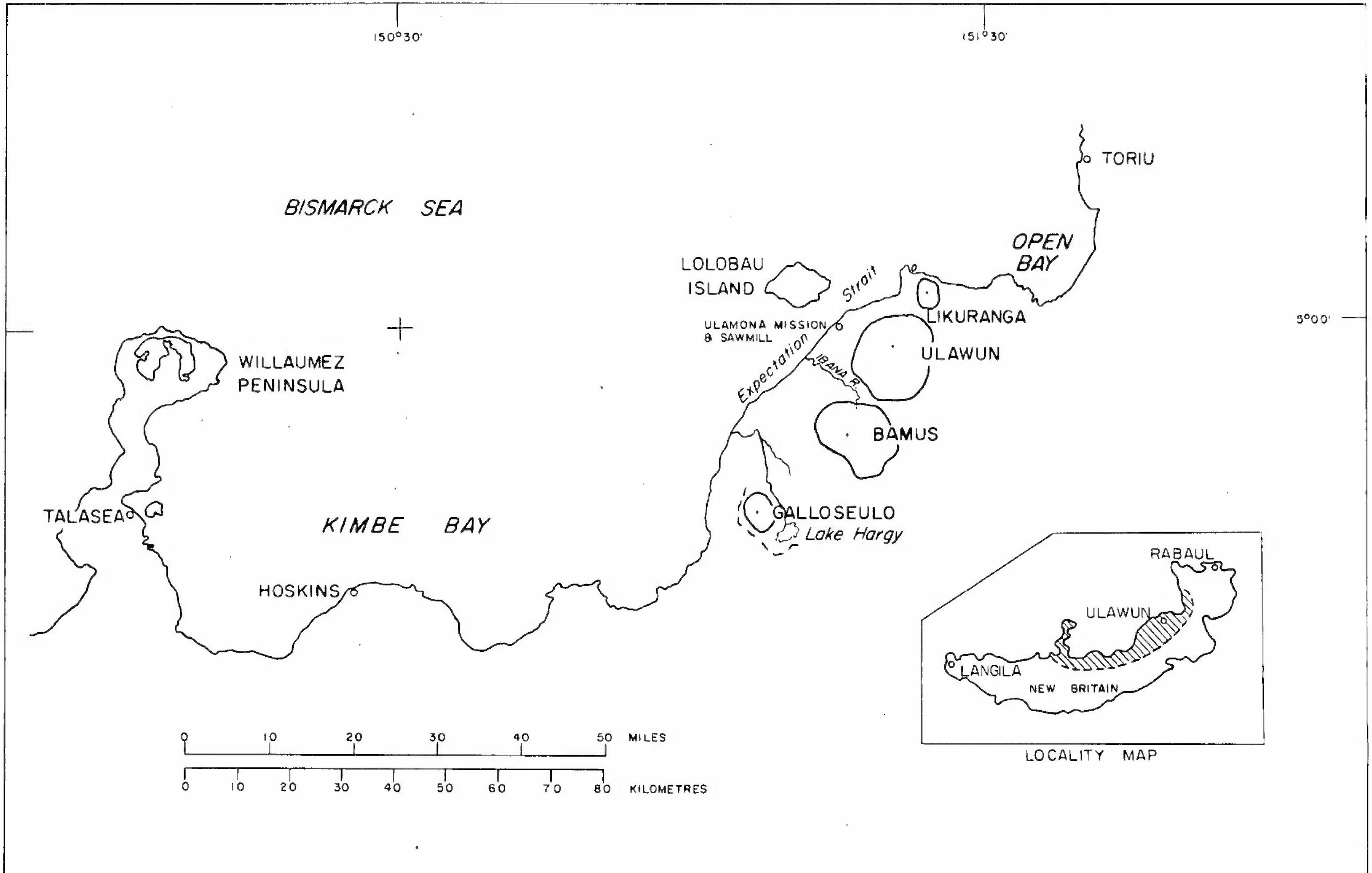

Figure 1. Index map of the north coast of New Britain

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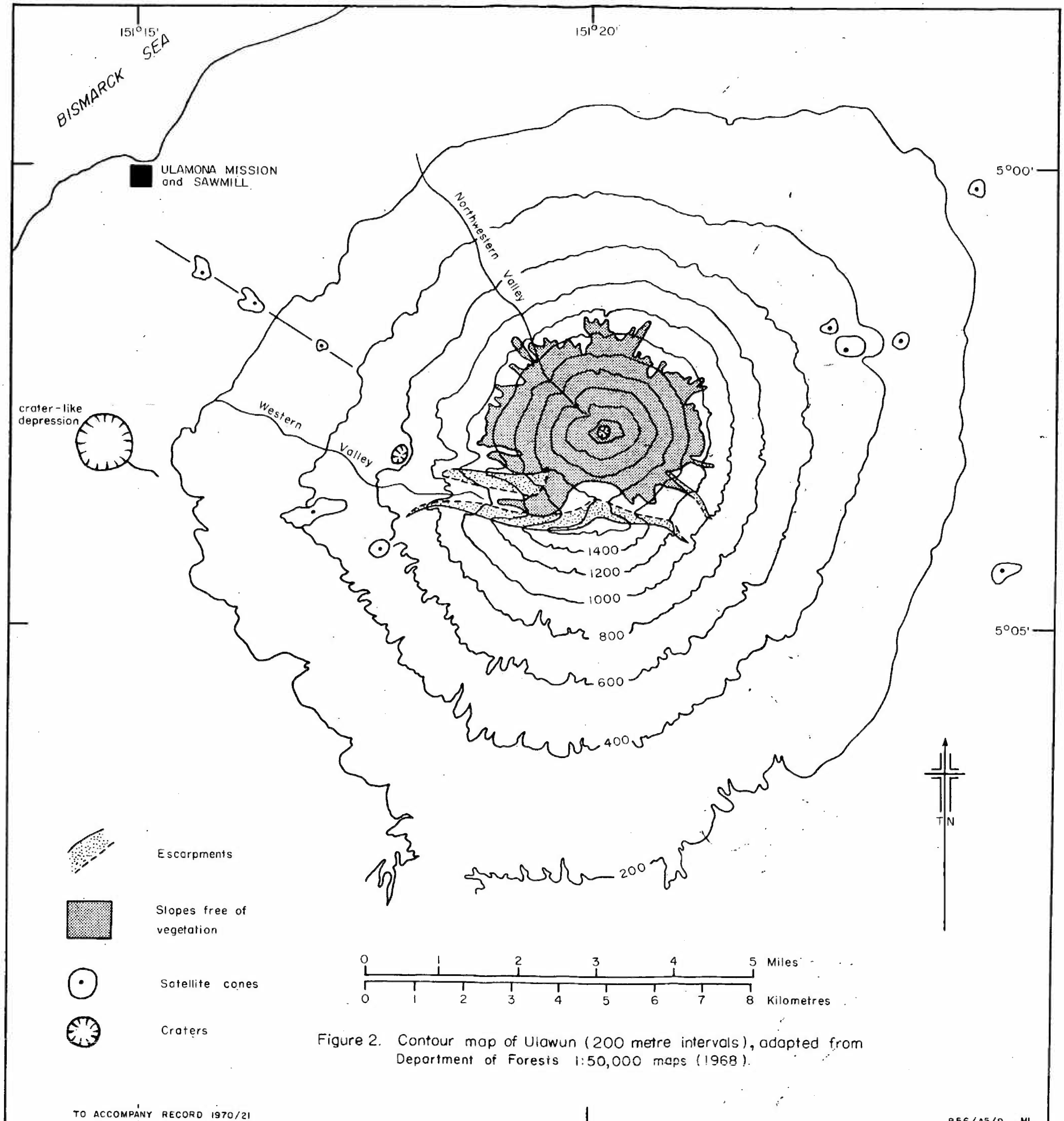

Figure 2. Contour map of Ulawun (200 metre intervals), adapted from Department of Forests 1:50,000 maps (1968).

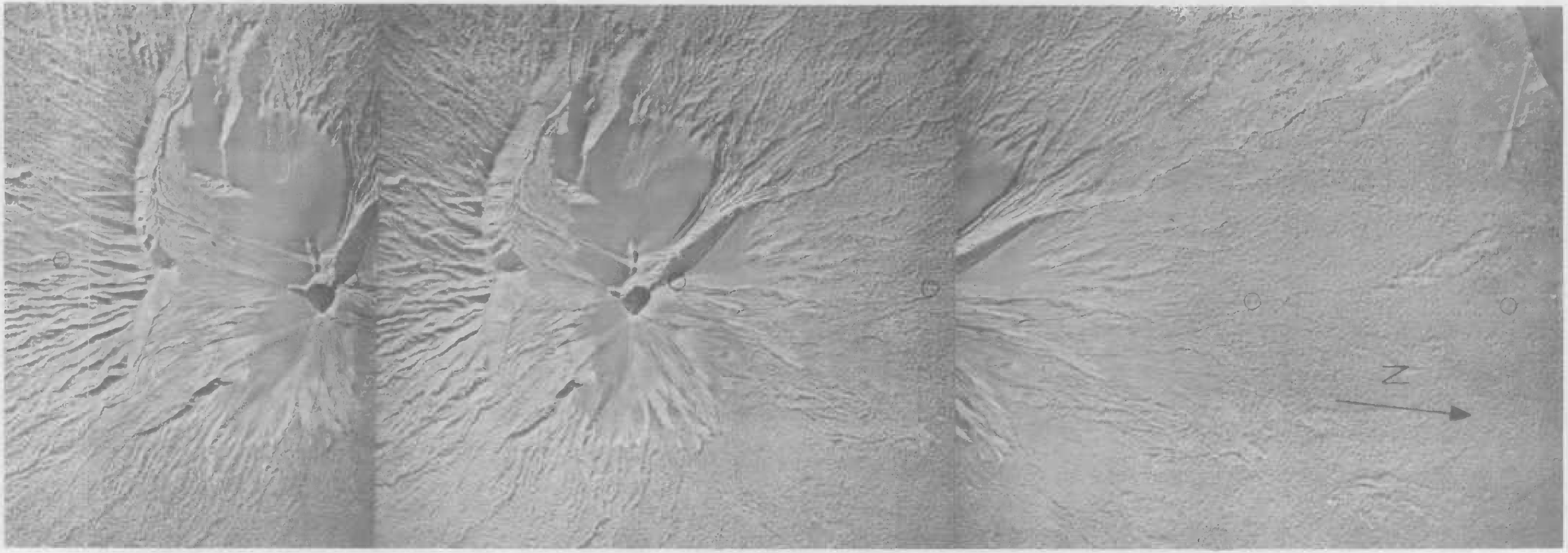

Figure 3: Stereoscopic pairs of air-photographs showing summit area of Ulawun and coastline. (Taken 17/6/48).

Figure 4: Ulawun from the southeast, showing east-west escarpment, scoria flows below the summit crater, and, in the distance, Lolobau Island. (Taken 19/3/69).

Figure 5: East-west escarpment — from the southwestern bomb-covered slopes of the younger cone. (Taken 25/3/69).

Other files at the Observatory include letters and telegrams from various observers who, from time to time, have reported on the eruptive events of Ulawun.

During the regional geological mapping of New Britain (February to May, 1969) ten days were spent at the summit region of Ulawun. A Bell "Jetranger" helicopter relayed the writer and two carriers to the rim of the summit crater on the morning of March 19th. Base camp was established on March 20th at 1000m. above sea-level, just above the forest line on the north side of the Western Valley, from which traverses were made each day. A helicopter pad was constructed, allowing the camp to be supplied with stores and a third carrier on the 22nd, and with three replacement carriers on the 25th. On the 27th, camp was moved to near the south side of the Northwestern Valley, just within the upper limit of the forest, and the next day Ulamona Mission was reached. During September, 1969, additional samples were collected from coastal exposures and the lower part of the Northwestern Valley.

3. EARLY VOLCANO.

Exposures of the early volcano are limited. The best outcrops are in the Western and Northwestern Valleys and, to a lesser extent, in the wall of the east-west escarpment and a prominent south-facing cliff opposite the western end of the escarpment (figure 2).

From a distance, the wall of the east-west escarpment shows a crude terracing probably caused by thin lava flows beneath the soil cover dipping to the south or southwest. Exposure is poor and, for the most part, inaccessible, but in places coarse, clastic deposits with large boulders may be observed from the base of the escarpment; these fragmental deposits are probably intercalated with lava flows. Below the highest point on the escarpment rim a dyke dips northeast at 70 to 80°, trending toward the summit of the escarpment.

In the cliff opposite the western end of the escarpment one prominent exposure, about 50m. high, shows massive deposits of unsorted scoria, with some ash, much of it deeply oxidised to a vivid red colour. There is a crude apparent dip of about 30° to the west (the true dip is probably to the northwest). A 3m.-thick basic dyke cuts across the exposure, and from it a sill extends to the west conforming with the apparent dip of the scoria. Other discontinuous, scoriaceous stringers of lava are probably spatter horizons.

For about three kilometers in the Western Valley, between 675m. and 1075m. above sea-level, water-worn outcrops reveal structures of the interiors of lava flows belonging to the early volcano. Clastic textures, caused by fragmentation of the lavas during flowage, are common (figure 7). The clasts range in diameter from less than a centimeter to about 2m., and are composed of fine-grained basic lava which, in most places, is porphyritic and slightly vesicular. Other clasts are dark, highly vesicular cinder fragments. The matrices vary from reddened, highly vesicular scoriaceous material to uniform, dark, continuous lava that almost certainly represents reconstituted, brecciated groundmass. Typical exposures, therefore, show light-coloured lava clasts in a darker, continuous lava matrix, studded with black cinder fragments.

The shapes of the clasts are highly variable. Those less than about 10 cm. in diameter are equant with a spherical coefficient averaging about 0.7, and a variable roundness coefficient averaging about 0.5.* Larger clasts, in particular those more than 0.5m. in diameter, are convolute, some of them with flow-banding, and others with gaping tension gashes formed by distension during flow. Many of these larger fragments have poorly defined, irregular margins, with smaller incipient clasts arrested in various stages of breaking from the parental lava fragments. There is a complete range between larger clasts (1-2m. in diameter) and masses of lava which may be regarded as part of the main unfragmented body of a flow.

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* Visual estimation in the field using the roundness and sphericity chart of Krumbein & Sloss (1963).

The fragmental lavas were probably formed by an autoclastic process, similar to that proposed by Curtis (1954) for andesitic breccias in the Mehrten Formation of the Sierra Nevada, California. Slight vesiculation of andesitic lava flows...

> "...so increases the viscosity that the magma can no longer adjust internally by flow with sufficient rapidity to keep pace with the inexorably moving lava from behind. Large joints or fractures develope...along which differential movements may cause slight dilation. For a brief instant, confining pressure drops to almost zero along dilated joints, and gases in vesiciles immediately adjacent to the surfaces of joints... expand so rapidly in the direction of reduction of pressure that they cause spalling along the joint surfaces..." (Curtis, op. cit., p. 469).

In contrast to the Mehrten "autobreccias", parts of the Ulawun fragmental lavas appear to have been modified after fragmentation. Laminar movement of the fragmental mass caused the larger, still fluid clasts to become distorted, and parts of the highly scoriaceous matrix to collapse and reconstitute to continuous lava.

The upper and lower surfaces of the fragmental lavas are not exposed, and their dips are therefore uncertain. However, the attitudes of several unfragmented flows, 30 cm. to 1m. thick, many of them with scoriaceous tops and bottoms, are clearly displayed in the Western Valley. The dip of these lavas is variable, both in direction and magnitude. One flow, for example, dips 39° to N 205°E, and becomes almost vertical a few meters to the west. Most measured dips are to the northwest, ranging from 25° to 60°, but others are between N345°E and N15°E, and range from 40° to 50°. At 850m. above sea-level, at the top of an almost vertical 30m. drop in the Western Valley, a more-or-less horizontal layer of non-vesicular, porphyritic, unfragmented basic rocks is exposed. This layer is either a sill or a thick lava flow (sample 0079 in Table 1).

The most complete section through the flanks of Ulawun is in the Northwestern Valley (the valley ascended by Fisher and Stehn in 1937). Here, a deep gorge with precipitous sides falls steeply from the summit crater, and at about 1220m. above sea-level parallels a series of smaller gullies which fan out and disappear below 1170m.

The Northwestern valley exposes lava flows and intercalated scoria and ash for most of its length, down to about 370m. above sea-level. Most of the lava flows are thin (up to 2m. thick), and many of them have flowed several kilometers from their presumed source near, or at, the present central crater. Fragmental lavas of the type observed in the Western Valley are also exposed.

In descending the Northwestern Valley, progressively older flows are revealed as the slopes of the mountain side are everywhere steeper than the dip of the lava flows beneath them. For example, at the head of the valley beneath the summit crater, the slope of the cone is 33° and lavas in the gorge sides dip at about 12°; or again, beneath the forest-line, where the outer flanks slope at less than 15°, the underlying lavas are more or less flat-lying.

Locally, the dips of lavas in the Northwestern Valley are variable, and the bases of several lava flows are unconformable on the underlying bedded clastic layers (figure 6). These features indicate the irregularity of the surface over which the lavas flowed: the irregularities are probably due to erosion channels in the unconsolidated clastic deposits which mantle the hummocks, ridges, and flow edges of underlying lava flows.

Figure 6: Lava flows of irregular thickness, and interbedded reworked scoriae, lapilli, and ash (with current bedding), in Northwestern Valley.

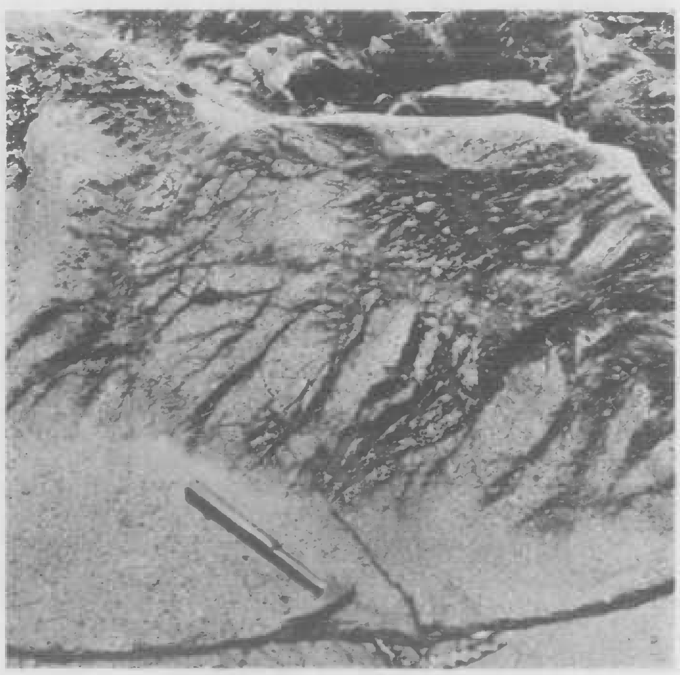

Figure 7: Fragmental top of flow in Northwestern Valley, showing - from bottom left to top right - transition from massive lava to zone of dilatational cracks, to fragmental rock.

4. FORMATION OF ESCARPMENTS, RAVINES, AND RIDGES.

The symmetry of Ulawun is broken by a number of escarpments, ravines and ridges (figure 2). The most prominent of these is the east-west escarpment on the southern flank that developed before the younger cone was constructed.

The origin of most of these topographic elements is problematic, for there are no clear-cut field criteria to distinguish between: (1) elements formed solely by erosion (and other processes of mass-wasting); (2) those produced by cauldron- or graben-like collapses into an underlying magma chamber; (3) those resulting from differential scouring of volcano-tectonic lines of weakness; (4) those formed by combinations of these process. Erosion of poorly-consolidated volcanic fragmental deposits free from protective vegetation cover is notoriously rapid in tropical latitudes, but its effect in producing escarpments and ridges on volcanic cones has to be contrasted with the role commonly played by local faulting and collapses in the roofs of magma cupolas.

The only deep ravine on the high parts of the mountain is the striking V-shaped notch of the upper Northwestern Valley. The ravine is in almost direct line with a southwest-facing escarpment on the south-east flank of Ulawun (figure 2). This escarpment is up to 60m. high, and its rim dips 26° from 1580m. above sea-level towards the southeast, terminating about 100m. below the upper limit of the rain forest. The alignment of the Northwestern Valley with the escarpment implies a linear, northwest-southeast fracture through the summit crater, and it is therefore concluded that the deep ravine northwest of the summit crater may be fault-controlled. Preferential erosion along the fault trace may have initiated rapid downcutting.

Fisher (1957) described the prominent, east-west escarpment on the southern flank as a "remnant of an old caldera now almost completely filled by the present cone." This interpretation is supported by the double-arc outline of the escarpment in plan (figure 2) which is strongly reminiscent of the embayments characteristic of many caldera walls (for example: Santorini caldera, Greece, and Crater Lake, Oregon (Williams, 1941); Menengai caldera, Kenya (McCall, 1957). However, the escarpment on Ulawun does not appear to be part of a typical caldera ring fault as it does not curve around the mountain; instead, it falls away to the east and west without significantly changing direction. There is no break in slope on the western, northern, or eastern sides of the volcano which might represent a mantled caldera rim, and no caldera ring fault is exposed in the Northwestern Valley.

One explanation is that a caldera may have been present, but that it was drastically modified by large-scale erosion, and remnant features on the eastern, northern, and western sides of the volcano were completely concealed by later volcanic products. Concealment would also have been more complete if the northern part of the caldera rim had been lower than the rest of the escarpment. Hawaiian calderas, on the summits of low-angle shield volcanoes, have rims which vary little in altitude from one part of the escarpment to another; but in the case of a steep-sided cone such as Ulawun, slight eccentricity between the axis of the volcanic cone and the centre of the caldera will produce marked differences in height. It is possible, therefore, that the centre of the Ulawun caldera was slightly north of the volcano's central axis, and that erosion and mantling of the northern part left a high remnant ridge to the south.

Another interpretation is that the east-west escarpment represents the coalescent, southern sides of two large erosion valleys, whose northern sides are hidden beneath the younger cone. Erosion on a colossal scale was claimed to have scoured deep valleys on Manam Volcano (Taylor, 1958) and Reunion Island, Indian Ocean (Upton and Wadsworth, 1965). These examples were quoted by Blake and Miezitis (1967) who also described three large amphitheatre-headed valleys on Balbi Volcano, Bougainville Island, two of which were believed to be headed by old "explosion craters." The rainfall catchment area for the postulated erosion valleys on Ulawun is only about 13 sq. km., and although substantial erosion has clearly taken place, it is doubtful whether this small area could produce sufficient run-off to erode a topographic feature as large as the east-west escarpment. If "explosion craters" were originally present then their remains have been totally removed by erosion or concealed by later deposits.

Several calderas in the Basin and Range Province, Nevada, and the San Juan mountains of New Mexico and Colorado, have central uplifted domes straddled by linear fault grabens similar to the structures capping salt domes (see, for example, Smith & Bailey, 1969). It is possible that the escarpment on Ulawun could be the southern fault scarp of a linear graben extending across the warped summit area of the volcano. The northern part of the graben may be hidden beneath the younger cone, but parts of it may be represented by the south-facing cliff opposite the western end of the east-west escarpment and, possibly, also by the northwest trending cliff in the southeast for which a fault-controlled derivation was argued earlier.

Thus, either collapse of a linear graben or cauldron subsidence seem the most likely explanations for the origin of the escarpment. If the escarpment was once part of a caldera, then erosion has severely modified it. It is believed unlikely that the escarpment was formed entirely by erosion.

5. YOUNGER CONE & SATELLITE VENTS.

The distinction between the "early" and "younger" cones is arbitrary. Although on the south side of Ulawun the vegetation-free slopes of the "younger" cone rise distinctly from the base of the forest-covered east-west escarpment (figure 2), elsewhere, the products of the younger cone appear to be conformable with those of the earlier volcano. Hence, a strict two-fold division into "earlier" and "younger" deposits is not meaningful. If the east-west escarpment is a remnant of a caldera, then the terms "earlier" and "younger" are synonymous with "pre-caldera" and "post-caldera". However, as concluded in the previous section, the presence of a caldera cannot be definitely established and these terms are also impractical. For the purpose of this account, therefore, the "younger cone" will be considered as that part of the mountain above the upper limit of the rain forest (figure 2).

The slopes of the younger cone increase from about 25^{0} at the forest line to a maximum of 37^{0} below the summit crater. As shown by the contours in figure 2, the younger "cone" is not strictly conical: its flanks appear roughly planar, and they intersect in rounded spurs.

Most parts of the flanks of the younger cone are mantled by thick deposits of unconsolidated, fresh scoriae, lapilli and ash, much of it representing the products of explosive eruptions during the past ten years. The northern slopes are covered with a continuous blanket of ash and lapilli. On other slopes, however, a hard crust of weathered volcanic debris is revealed beneath the unconsolidated deposits.

This hard crust, which was observed by Fisher and Stehn in 1937 (Fisher, 1937), appears to have formed by exposure of the ground surface to the atmosphere. Rain and sun (and probably chemical weathering) have combined to enhance disintegration of volcanic debris which, when waterlogged and exposed to the sun, is baked and hardened to a resistant layer. This layer, when dry, does not absorb rainwater easily and, during torrential downpours, water flows rapidly over its surface. After longer periods of rain, however, the crust becomes saturated; it begins to erode, and the less consolidated underlying deposits are rapidly scoured.

Exposures of rock within the younger cone are restricted to the upper part of the Northwestern Valley and the walls of a few shallow gullies on the southern and southeastern slopes. In the Northwestern Valley, lava flows and scoria and lapillus layers are exposed to a depth of over 30m. Vivid red, oxidised material is found 2 to 3m. feet below the surface, particularly in beds with a large ash or lapillus component. A prominent, sill-like layer of lava, which marks the head of the Northwestern Valley, is either a cone-sheet intrusion or, more likely, a lava flow.

In the walls of gullies on the southeastern slope of the younger cone, limited exposure reveals evidence of fluvial reworking of pyroclastic material: false bedding (dips up to 44^{o}), eroded bedding surfaces, and well-sorted, fine-grained layers are all common.

The gullies on the southeastern slopes are filled with fresh, black scoria, extending in tongue-like masses from the rim of the summit crater to below 1450m. These masses have well-defined flow fronts, and from the air they are indistinguishable from lava flows (figure 4). As the scoria tongures do not appear on air-photographs taken in 1948 and 1965 (see Appendix I), it is concluded they formed during the eruptive activity of January, 1967 (see section 8).

The scoria tongues almost certainly represent the deposits of hot pyroclastic flows. Hot scoria must have landed on the steep, upper slopes of the cone, and, cushioned and buoyed by hot volcanic gases and heated air, moved downslope in avalanches. The fragmental flows were not nuées ardentes: the clastic components were almost exclusively scoria, and they moved as hot flows for only limited distances down the steeper flanks, their flow-fronts terminating on slopes greater than 20^{o}.

Compared to the mass of volcanic products erupted from the central vent, the volume emitted from satellite vents on Ulawun is insignificant (less than 1% by volume). The distribution of these satellite vents is shown in figure 2; most are marked by steep-sided cones, but one appears to be a pit crater.

South of Ulamona Mission, three prominent satellite cones form a chain (trending northwest-southeast, more or less radially to the volcano) which marks a flank fissure. At the coast, west of Ulamona, lava is exposed in a restricted area in direct line with the chain of satellite cones (figure 2); the lava probably represents flows erupted from the flank fissure.

6. SUMMIT CRATER

The summit crater of Ulawun is about 400m. wide. In plan it has the approximate outline of a parallelogram with each straight side parallel to the contours of the contiguous flanks of the younger cone (compare figures 2 and 8). The highest parts of the rim are on the northern, eastern, and southeastern sides. The summit of Ulawun, on the eastern rim is 2200m. above sea-level**, and the deepest part of the crater, 130m. below the summit, is slightly east of the centre of the depression. The two lowest points on the rim are at the head of the Northwestern Valley (2100m) and on the south rim (2150m). At both of these saddles, and at the western corner of the crater, subsidiary depressions outside the main crater suggest the presence of old satellite vents which may have developed on a ring fracture at the crater rim (figure 8).

Scoria, bombs, lapilli, and ash comprise the bulk of exposures on the inner walls of the crater (figure 9). A few thin layers of lava are also exposed in the western crater wall and in the cliffs of the depression at the head of the Northwestern Valley. Pyroclastic debris mantles most of the inner part of the crater, and talus is banked beneath the steeper walls. Four types of pyroclastic ejecta may be distinguished in the vicinity of the summit crater:

(1) Scoria is by far the most common type. Fragments range from 1m. in diameter down to lapillus-size. There is a tendency for many of the larger fragments to be plate-like. The rough surface of the scoria clasts gives cohesion to the unconsolidated surface deposits, tending to inhibit talus slides down the inner slope of the crater and the flanks of the younger cone.

**This value was read from a pocket altimeter, and is about 100m. lower than the altitude given on the United States Army 4":1 mile map (1943). The pocket altimeter value is uncorrected for diurnal pressure variations, and is probably inaccurate. Fisher (1937) gives the altitude as 2,260 metres.

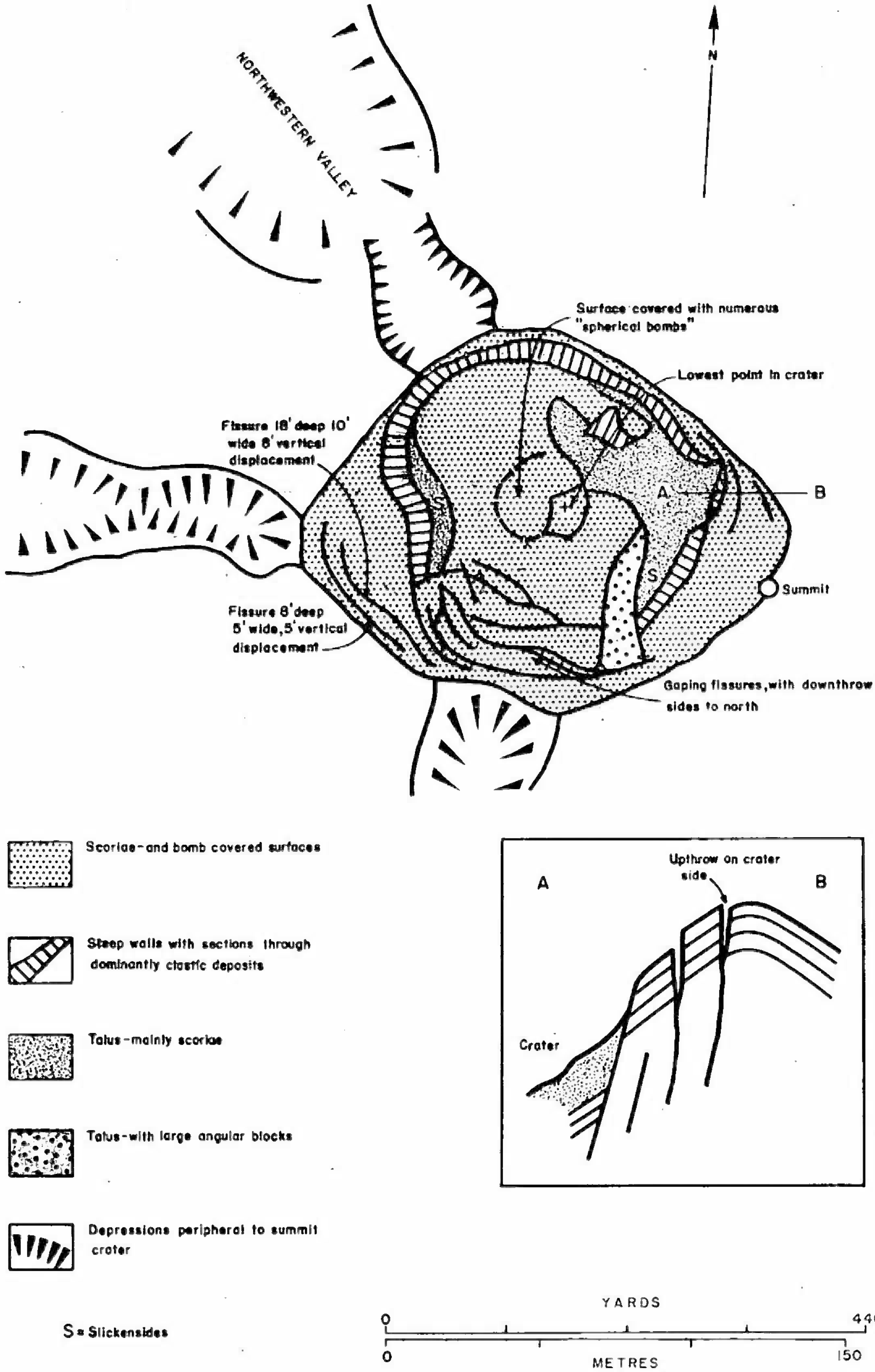

FIGURE 8. Simplified map of summit crater of Ulawun (from a field sketch 19/3/69)

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(2) Spindle and ribbon bombs are the largest of the four types of ejecta. Few of the bombs are complete, and many - particularly the smaller ones - appear to have broken when they landed. The complete spindle bombs range in length from a few centimeters to about 1m; the largest example measured was 2.25m. long. The bombs consist of co-axial cylindrical layers of vesicular lava, tapered at both ends, with a prominent lineation parallel to the axis of the spindle. A few are disc-shaped, and some have flanged girdles. One striking, though atypical, example is a spindle bomb that landed with its axis almost at right angles to the ground surface; the layers at the upper end of the bomb splayed and produced a shape reminiscent of a tulip with unfurled petals. The ribbon bombs tend to be smaller than the spindle bombs, and many of them may have been produced by the disintegration of the outer layers of spindle bombs as they were flung through the air.

(3) "Spherical bombs" are conspicuous, but they are less common than the spindle variety. The bombs range in diameter from a few centimeters to 0.5m. When struck by a hammer, a peripheral layer easily falls away, and the cores break along numerous joint surfaces. These near-spherical bombs are particularly abundant on the floor of the crater where they may have accumulated by rolling from higher parts of the crater wall (figure 8).

(4) Ash and dust are present in subordinate amounts at the surface in the crater area. During eruptions, much of this finer material must have been carried far from the vent and deposited on the lower flanks of Ulawun. Ash and dust are absent on surfaces littered with bombs and coarse scoria: the fine debris appears to have been washed down the spaces between larger clasts, producing a "lag" deposit.

The caldera rim on the western, southern, and eastern sides is cut by a series of en-echelon, concentric fissures (figures 8 and 10). These are subsidence structures formed by collapse of the inner crater walls towards the centre of the depression. At the crater rim the fissures are dilatational with small vertical displacements. Displacements are greater on fissures on the south-western wall. About half way down the crater some of the fractures show no dilatation, and fault faces with slickensides are exposed (figure 8). Small rock falls from these fault faces were observed on March 19th, 1969.

Fisher (1937) noted the concentric fractures on the summit crater in August, 1937. He also described a continuous steam cloud that rose from "...a vertical neck 30-40 metres (100-130 feet) in diameter, to which no bottom can be seen". J.G. Best, a former volcanologist at the Rabaul Observatory, made an aerial inspection of the summit of Ulawun on October 7th, 1951, and observed that the vertical neck had been completely filled, and there was no steam cloud (unpublished report, Rabaul Volcanological Observatory). Fisher (1957) later examined the 1948 air-photographs of Ulawun which suggested to him "...that some reaming out of the crater by volcanic activity had taken place between ....August 1937 [and 1948]...". He also noted that "...the inner walls had subsided forming a fairly symmetrical basin."

During March, 1969, the lowest point of the crater floor was covered with scoria and talus boulders up to 5m. across, and the vertical neck described by Fisher (1937) was nowhere in evidence. Fumarolic activity was restricted to drifting columns of water vapour, most of which emerged from the peripheral concentric fissures at the crater rim. No fumaroles were present at the bottom of the crater, and hydrogen sulphide and sulphur dioxide fumes were not detected. Small quantities of a white crystalline sublimate were present, but sulphur was rare.

7. OUTWASH DEPOSITS.

Thick outwash deposits mantle the lower slopes of Ulawun. This detritus consists almost entirely of derived pyroclastic material washed down from the steep upper slopes of the volcano. Evidence of reworking of the material can be found high on the upper slopes of the younger cone (section 6), and it is probable that throughout the growth of Ulawun most of the ash and lapilli that fell on the volcano subsequently

Figure 9: Inner eastern wall of summit crater, with downwarped pyroclastic beds mantling the rim. Water vapour issues from a fumarole on the extreme right. The vapour above the light-coloured hydrothermal area on the left is atmospheric cloud. (Taken 19/3/69).

Figure 10: Western rim of summit crater from the north; covered by volcanic bombs and scoriae, and showing two, peripheral, dilatational fissures, whose dimensions are given in Figure 8. (Taken 19/3/69).

moved during periods of heavy rainfall. The outwash debris forms flat-lying beds near the coast-line, and it undoubtedly extends below sea-level, where marine agencies have probably dispersed the material farther from its terrestial source.

Thick accumulations of outwash debris are present at the head of the Western Valley in the depression between the east-west escarpment and the southern slopes of the younger cone. Here, above the rain forest on the west side, several deep gullies with vertical walls reveal excellent sections through the outwash debris. The deposits dip to the west and are over 30m. thick. Bedding is crude, and is defined mainly by layers in which large blocks are concentrated. Some beds, 0.3 to 0.6m. thick, consist almost entirely of lapilli and ash, but most layers are poorly sorted, and contain a complete range from dust-and ash size particles to scoria fragments and rare blocks up to 1m. in diameter.

Further outcrops of outwash deposits are found below the forest line in the Western Valley. At 840m. above sea-level, about 20m. of sediment are exposed beneath an almost vertical drop of 30m. in the river course. Here, large-scale cross-bedding is observed with beds banked against the vertical drop. At 680m. above sea-level more cross-bedding is clearly displayed in outcrops almost 30m. high. Several river terraces, up to 1.5m. high, are present, and talus and landslip debris is inclined against the steep walls of the stream valley.

In the Northwestern Valley outwash debris is found both as surface deposits at the periphery of the volcano, and as intercalations with lava flows. The debris beneath lava flows represents material which was in the process of transport to lower levels when lava flowed over it, solidified, and formed a protective cover, thus preventing further transport of the underlying outwash deposits.

The Northwestern Valley has a V-shaped cross section down to about 600m. above sea-level. Below this the floor of the valley is filled with outwash detritus. At about 450m. the walls of the valley are only 1-2m. high, and the floor is 20 or 30 meters across and filled with debris dipping downstream at low angles. Between 450m. and 150m. the walls of the stream valley decrease in height and disappear, leaving an extensive alluvial fan which spreads down to sea-level. There is no single channel on the alluvial fan, and most of the waters that may fill the valley higher up the mountain, sink into the porous detritus below 150m. and thus do not drain directly into the sea.

All the streams on Ulawun are ephemeral. The rocks of the volcano are porous, and light rains are quickly absorbed into the volcanic pile. During extended periods of torrential rainfall, however, rainwater rapidly fills and moves down old stream courses, cutting new ones, and scouring out unconsolidated deposits. Lava flows are undercut and, in time, they collapse into the channel, and the detritus is swept downstream. Once the heavy rainfall ceases, the streams slow down, waters soak into the porous valley floor, and the courses become dry again. Thus, "flashflooding" is the main cause of erosion on the mountain, and also the means of transport of detritus to the periphery of the volcano and the sea.

8. ERUPTIVE ACTIVITY BETWEEN 1915 and 1967.

Introduction.

Ulawun is in a conspicuous position on the north coast of New Britain. It is close to regular air-line routes between Talasea and Rabaul, and numerous island cargo boats ply the inshore waters of the Bismarck Sea, serving various plantation and mission communities along the coastline. Few significant eruptions can therefore have gone unnoticed, and there is sufficent available information to reconstruct a history of eruptive activity.

After World War II, collation of data on volcanic eruptions in Papua and New Guinea was undertaken by the Volcanological Observatory at Rabaul. The following account is based on data assembled in File V.F./9A ("Mount Ulawan (The Father) & Mt Bamus (South Son)") and the Monthly Reports of the Observatory. It is essential to emphasise, however, that these data are not comprehensive. Many of the records are incomplete. Furthermore, most of the observations were made from Ulamona Mission Station and Sawmill on the western side of the volcano, and during the "northwest" or wet season (December to March), when winds blow to the east, emissions may not have been clearly visible from the Mission. Visibility may also be obscured for a large part of many days at other times of the year.

Most of the information on the eruptive activity of Ulawun was contributed by Father J. Stamm who first came to the Ulawun area in 1914. From Toriu and Ulamona Mission, Father Stamm observed all the important eruptions of the volcano up to 1965. Father Stamm is at present in retirement at the Central Roman Catholic Mission Station, Vunepope (near Rabaul), and he has read and criticised the following account. Comments were also made by Brother B. Rollef who has been at Ulamona Mission since 1937.

Activity between 1915 and 1960

In a letter, dated 4/5/61, to volcanologist G.A.M. Taylor at Rabaul, Father Stamm recalled the first recorded eruptive event of Ulawun in 1915. The year before the outbreak, when Stamm arrived at Toriu Mission and Sawmill, 30 miles northeast of the volcano across Open Bay (figure 1), he observed each day a plume of "smoke" from Ulawun, and when this emission ceased the local populace believed the volcano was moribund.

But in April, 1915, an eruption suddenly commenced: "At the beginning we could not see anything...there was a heavy Northwest storm, but we felt the ashes falling down, covering the ground three or four inches...Shortly after this I was awakened one morning by light of a fire, as I thought it to be at first...A column of fire [from Ulawun] rose high up in the air, as if a giant gun was fired straight up. Such a blast came every few minutes. At daytime fire could not be seen, only a black cloud that became shining white when the sun shun (sic) upon it." This activity lasted for a few days. Periodic outbreaks of "lesser violence" followed, and at times a fiery glow could be seen at night. During the entire eruptive period no ash reached Toriu, but inhabitants from the vicinity of Ulawun, who later visited Toriu, related how most houses had collapsed under the weight of ash; no large ejecta had fallen, and there had been no fatalities.

Father Stamm was stationed at Valoka, near Hoskins (figure 1), between 1924 and 1929, and he noted that during this time Ulawun showed almost continuous "emissions" which were similar to those produced late in 1960 (December Monthly Report, 1960). Ulawun remained in a "mildly active" state up to the beginning of 1941 (volcanologist J.G. Best in report dated 24/9/51; Fisher, 1957); Father Stamm and Brother Rollef (personal communication, 1969) both observed the last of these "mild" eruptions in January, 1941 (Fisher, op. cit.).

Fisher (1937, 1939b, 1940, 1957) mentioned a mild eruption from Ulawun in 1937, the year Rabaul was inundated by ash from Tavurvur and Vulcan craters in Blanche Bay (Fisher, 1939a). However, neither Father Rollef, nor any of the other Brothers who were at Ulamona in 1937, observed any increased eruptive activity of Ulawun during that year (personal communication, 1969).

Activity between 1960 and 1962

Reports of increased activity from Ulawun were received at the Rabaul Observatory in August, 1960. This activity followed twenty years of relative quiet during which only slight increases in the volume of steam emission were noted-in November, 1950, and between February 18 and 27, 1955. Reports from m/v "Stradbroke" (telegrams 27/8/51, 11/9/51) of increased activity in 1951 were not confirmed.

Mr. F. Kaard, District Officer, first drew attention to a report of new eruptions from Ulawun on August 19th, 1960 (radio message to Rabaul). This report was confirmed on August 20th by Mr. A. Savage, Master of the Administration vessel "Mangana", who described "Smoke rising to three or four hundred feet above the summit and drifting off in a banner extending to Lolobau." (letter to G.A.M. Taylor from volcanologist J.G. Best, 22/8/60). Mr Kramer, plantation manager on Lolobau Island, claimed the activity had been continuous for the previous three weeks (telegram 22/8/60), and that there had been earth tremors, none of which, however, was felt at Ulamona Mission. A QANTAS DC3 pilot reported to the Assistant Administrator in Port Moresby that "the whole crater was filled with smoke settling down on the southwest face of the mountain..." (telegram 23/8/60). No explosions were heard, and very little pyroclastic material - if any - appears to have been deposited on the lower flanks. On August 28th, Mr Kramer reported another tremor on Lolobau, at 1315hrs. G.M.T., which was recorded on the seismographs in Rabaul. Seismologist M. Mancini at the Volcanological Observatory, however, considers that this tremor was not of volcanic origin (personal communication, 1970).

Following a telegram on February 11th, 1961, from Mr Kramer on Lolobau Island, reporting more vigorous activity from Ulawun, an aerial inspection was made by a volcanologist from Rabaul. This confirmed that emissions had again increased, but it was noted: "...examination of the leeward slopes indicates any recent ash emissions have been light" (telegram 14/2/61) to the Assistant Administrator, Port Moresby.

Emissions of dark, presumably ash-laden, clouds and white vapour continued spasmodically up to November, 1962.

Activity in 1963

On March 17th, 1963, Ulawun entered a more intense period of activity that lasted into the middle of May. The eruptions were described in letters from Father Stamm to the Observatory, and in brief accounts in the Monthly Reports by volcanologist C.D. Branch who visited Ulamona Mission between April 16th and 22nd. The following tabulation summarises these data.

March 17	A large, black cauliflower-shaped cloud was observed above Ulawun in the early morning. By evening the emissions had diminished and the cloud was dark grey. Although the cloud appeared to be ash-laden, it did not drift, and no ash fell on Ulamona. No noises were heard and there were no earth tremors.
March 18 -19	Activity remained the same.
March 20	During the previous night small quantities of ash fell on Ulamona. Later in the day a sample of ash from heavier falls near the Ibana River, 13 km. southwest of Ulamona (figure 1), was brought to the Mission, and this was forwarded to the Rabaul Observatory. During most of the day Ulawun was concealed by clouds.
March 21	White vapour clouds were observed at first, but dark grey emissions were visible later. At 1445 hrs an earth tremor with a pronounced vertical component was felt at Ulamona.

March 22	In the early morning the grey-white vapour cloud was again observed. At 0800 hrs, there were black emissions (presumably ash-laden), but the "cauliflower shape" of the eruption seen on the 17th was not reproduced. Cloud concealed the mountain during the day, but by evening the familiar white eruption cloud was again revealed.
March 23 to the beginning of April	Activity remained the same. The white emission cloud was possibly a little more pronounced than in the weeks prior to the March 17 outbreak, but not nearly as strong as in the 1960-1961 period of activity.
April 8	An unusual "thick cloud ball" hovered above the mountain, the lower part of it, 60m. above the summit, absorbing vapour rising from the crater.
April 9	A black eruption cloud was seen at 0500 hrs. It was driven west towards Ulamona where there was a slight ash-fall. Later, the wind changed direction, and during the rest of the day a red-brown plume drifted away to the southwest. A Brother at Ulamona Mission felt a slight tremor at 0610 hrs, but this was not noticed by others.
April 10-11	The plume continued to drift to the southwest. During both days the mountain summit was concealed by cloud. On the evening of the 10th the plume was seen drifting to the southeast, and on the 11th the eruption column could be seen above the cloud level.
April 12	The emissions were weaker, but later that night some ash fell on Ulamona.
April 13-16	Activity was strong at 0900 hrs on the 13th, and again, at the same time, on the 14th; but by the 16th vapour emission had stopped completely.
April 17	A yellow-brown plume appeared again, extending from a dark grey vapour cloud, and drifting to the southwest.

April 18-30	On the 18th, the colour of the eruptive cloud changed to black, and ash fell on Ulamona. This ash-fall was the thickest observed at Ulamona during the 1963 period of activity. At 0830 hrs, there was moderate ash emission up to 3,600m., and "stronger explosions" took place every 2-5 minutes. This activity continued until the morning of the 19th, but at 1800 hrs only steam could be seen, rising to about 300 m. above the crater. This condition lasted until the end of the month. Branch recorded two possible tremors at Ulamona in five days between April 16-22.
May	On May 1st, another "cloud ball" was observed hovering high above the crater. During the night, a glow from the crater projected a white circular area of light onto the base of the cloud. On May 2nd, light blue-grey emissions were noted, but no glow or reflection appeared that night. The blue-grey emissions became stronger during the following days. A long grey plume could be seen trailing off, but this disappeared on May 17th.

No further ash emissions took place, although fluctuating steam clouds were given off at varying intervals until October, when the last report on the 1963 period of activity was filed.

Activity in 1967

On January 23rd, 1967, a message from Ulamona Mission was received at the Rabaul Observatory reporting that Ulawun had erupted the previous night, with "lava running for about one mile". This information followed a telegram on January 20th, reporting that for five successive nights a "steady glow" had been observed from the volcano. This eruption of Ulawun took place three days after an explosive outbreak from Langila volcano, west New Britain (figure 1).

The Ulawun eruption was short-lived. Brother F. Kleinelanghorst at Ulamona Mission recorded that the peak hours were between 2200 hrs on the 22nd and 1000 hrs on the 23rd (letter 25/1/67). During this time, ash fell on Ulamona to a depth of 10-12 mm., causing minor damage to houses and crops in nearby gardens. 6 to 8 km. east of Ulamona, at the foot of Ulawun, the deposit was reported to be 5-8cm. thick, and about 1.5km. up the mountain the ash fragments were observed to be larger (up to 8 cm. in diameter), and the layers to be thicker. A "big subterranean noise (like a thunderstorm)" was heard at Ulamona during the eruption, but no earth tremors were felt (letter 25/1/67 from Br. Kleinelanghorst). Light ash also fell on Lolobau Island, damaging gardens slightly, and collapsing structures (probably poorly contructed) at Mauga Plantation.

Assistant District Officer C.T. Campbell (Hoskins Patrol Post) examined the vicinity of Ulawun after the eruption to estimate the extent of damage to villages and gardens. In his report (31/1/67), Campbell recorded that no ash had fallen on villages east of Ulawun, but during the eruption people had fled from Ubili village, near Ulamona, to the Mission, and all but three of the population of Nuau had moved to Nantambu.

Many of the volcanic bombs and scoria fragments which litter the summit area and upper western flanks of Ulawun were probably ejected during this eruption (see section 6). C.T. Campbell recorded: "...reports of large rocks being blown high above the crater and then falling back inside." Brother Rollef (personal communication 1969) also described showers of incandescent bombs which rained down on the upper slopes of the cone, and one exceptionally large boulder which rolled down the northern flank at high speed, shedding a trail of glowing particles, and plunging into the forest.

On January 23rd, the day on which the report was received of lava flowing on the western flank, volcanologist G.W.D'addario made an aerial inspection of Ulawun. He found no evidence of a recently erupted lava flow. As A. Renwick, Senior Resident Geologist in Port Moresby, commented in a letter to the Department of the Administrator (24/1/67), the false report may have originated if incandescent bombs rolling down a steep slope had been mistaken for flowing lava.

Throughout the remainder of 1967, occasional reports were received of the periodic appearance of dark grey to black emission clouds above the crater. During June, for example, clouds were observed on several days, rising 30-100m. above the summit, but lasting only 1 or 2 hours (letter 1/7/67 from Br. Kleinelanghorst). The last eruptions recorded in 1967 took place on December 27th and 28th when the same dark grey emission clouds appeared.

The 1967 eruption appears to have been the most spectacular of all the eruptions observed from Ulamona Mission. The red glow in the night sky, and the incandescent bombs which were flung out from the summit crater, appear to have impressed observers much more than any earlier eruptive event from Ulawun. Father Stamm, who viewed the violent 1915 eruption from Toriu, did not observe the 1967 eruption, and it is not possible therefore to compare the two events.

Conclusions

1. The eruptive events of Ulawun, recorded between 1915, and 1967, have been mildly explosive. The eruptions in April, 1915, and January, 1967, appear to have been the most violent.

2. Eruptions have produced pyroclastic material in sufficient quantities to cover various parts of the mountain slopes with thin veneers of ash and lapilli. No lava flows have been erupted.

3. Although data on most of the eruptions is incomplete, each period of activity appears to have had a similar life-history. The initial explosions seem to have been the most violent, and they appear to have followed periods of inactivity; less violent succeeding eruptions were periodic, and some continued for several months after the initial outburst.

4. The direction in which an ash-laden cloud may drift is not consistent, and on occasions local meterological conditions seem to have prevailed over the regional wind regimes characteristic of the north coast of New Britain. For example, during the eruption of January 23rd, 1967, ash was deposited on the west and northwest sides of the volcano. At that time of the year, however, winds of the northwestern season sweep east across Kimbe Bay, and ash would therefore have been expected to fall on the eastern flanks of the volcano and not on the western side.

ADDENDUM

On January 16th, 1970, after a week of mild initial activity, Ulawun commenced a large-scale eruption. Fountains of incandescent material were erupted from the summit vents, and a voluminous vapour column was produced which rose to 6000m. above sea-level.

At 0415 hrs on January 22nd, a basaltic nueé ardente was discharged, followed by lava flows which travelled the path of the nueé, descending the Northwestern Valley to 460m. above sea-level.

At 2000 hrs. on January 26th, lava flows were erupted down the southern slopes of Ulawun; they turned west at the east-west escarpment, and then moved down the Western Valley. The emission of lavas was accompanied by the eruption of three nueés ardentes which descended in the same direction as the lava flows.

The summit crater described in section 6 of this report was modified and buried by the products of the eruption.

The new activity is being studied by G.A.M. Taylor and by W.D. Palfreyman and R.A. Davies of the Rabaul Volcanological Observatory, and is to be the subject of a separate report.

9. PETROLOGY:

Fifty-eight rocks from Ulawun volcano have been examined in thin section. They are mostly porphyritic basic lavas in which plagioclase is the most common phenocryst. In many of the rocks, a few percent of ferromagnesian phenocrysts (pyroxene and olivine) are also visible in hand specimens. Modal analyses of 32 samples are given in Table 1, and their localities are listed in Table 2.

The samples in Table 2 are divided into six groups which correspond to different sampling areas on the volcano. The relative ages of the six groups are unknown. However, rocks of group 5 are undoubtedly the youngest, and those of groups 1 and 4 are probably the oldest. The flank fissure lava flow at Ulamona (group 6) is probably a recent lava that post-dates groups 1 to 4.

Plagioclase is the most abundant phenocryst, and, in the majority of the samples, it comprises between 10 and 40% (by volume) of each rock. Sample 0826 contains 41% and samples 0065B and 0059 less than 10% of plagioclase phenocrysts.

The feldspar phenocrysts vary widely in size and habit. Many large crystals up to 4 mm long, contain abundant inclusions of groundmass material; smaller phenocrysts tend to be inclusion-free. A few glomeroporphyritic aggregates of plagioclase, with or without ferromagnesian phenocrysts are present. Many feldspar phenocrysts show normal and oscillatory zoning. The compositions of most grains (determined by the albite twin extinction method) fall in the labradorite range (An50-70).

Augite is the most common pyroxene phenocryst, and is present in all but two of the samples examined (the two exceptions are 0823 and 0826 of group 6). Most augite phenocrysts are pale brown and euhedral; many are twinned, and a few are slightly zoned. Aggregates of augite, with or without other phenocryst minerals, are commonly present.

Pigeonite is a second variety of clinopyroxene found as phenocrysts. It is present in many of the samples, but, in most, is less than 1% by volume. (Sample 0093 contains the highest percentage of pigeonite: about 3%).

The "pigeonite" is distinguished from augite by its small 2V**, lower birefringence, and compositional zoning which, in some rocks, is particularly distinctive. Some pigeonite grains show concentric zoning. Others exhibit planar zones that parallel the prism faces of the crystals. Extinction angles are greatest in the outer zones.

During modal point-counting, it is too time-consuming (and not always possible) to obtain interference figures for all the clinopyroxene phenocrysts. Hence, the modal percentages of pigeonite in Table 1 are only approximate, as they rely on such unsatisfactory criteria as zoning and birefringence for identification of the pyroxene.

Hypersthene (distinguished from other pyroxenes by its straight extinction, low birefringence, and distinctive pale green to reddish brown pleochroism) is commonly present as phenocrysts. In several samples, large hypersthene phenocrysts are rimmed by grains of augite, and in a few specimens (for example 0090) hypersthene and augite are intergrown.

**Pigeonite is recognised optically by its small 2V (see, for example Deer, Howie & Zussman, 1963, vol. 2, p. 143). MacDonald (1968) and Stice (1968), however, recently analysed pyroxenes with small 2V, and showed them to be ferroaugites. Electron micro-probe analyses of the zoned pyroxenes in the Ulawun rocks are necessary to determine their true compositions.

Some smaller, lath-shaped hypersthene crystals also have overgrowths of clinopyroxene which, in many cases, are restricted to the two long edges of the orthopyroxene, giving a distinctive, "sandwich" -type configuration (for example, 0093 and 0094). Most of these hypersthene grains are intermediate in size between phenocrysts and groundmass grains. The mantles of clinopyroxene are probably augite, but few suitable interference figures could be obtained (owing to the fineness of grain), and the pyroxene could be pigeonite.*

<u>Magnesian olivine phenocrysts</u> (optically +ve and colourless) are common to all but a few of the samples, although in many cases they do not exceed 1% by volume. Olivine is particularly common, however, in rocks of group 4. As illustrated by figure 11, there is an inverse relationship between the proportions of olivine and hypersthene phenocrysts.

In rocks with a coarsely crystalline groundmass the olivine phenocrysts have rims of pigeonite. This feature suggests that the rocks have silica-saturated, tholeiite basalt compositions in which the magnesian olivine bears a reaction relationship with Ca-poor pyroxene (MacDonald and Katsura, 1964). In some rocks with a fine-grained groundmass (and no rim of pigeonite to the olivines; see asterisk in Table 1), the olivine phenocrysts show rounded or embayed outlines suggestive of resorption. However, in other rocks, the olivine grains are euhedral. Some olivine phenocrysts have crudely skeletal outlines, similar to those described by Drever and Johnston (1957).

In several rocks, grains of iron-titanium oxides are either concentrated at the edge of, or completely pseudomorph, olivine phenocrysts. These zones of iron-titanium oxides are described and discussed more fully in Appendix B.

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* Muir & Long (1965) described Hawaiian basalts containing hypersthene phenocrysts with jackets of clinopyroxene which were "discontinuous and...mainly confined to the prism faces of the orthopyroxene...". They believed that the clinopyroxene was pigeonite, but electron micro-probe analysis showed it to be augite.

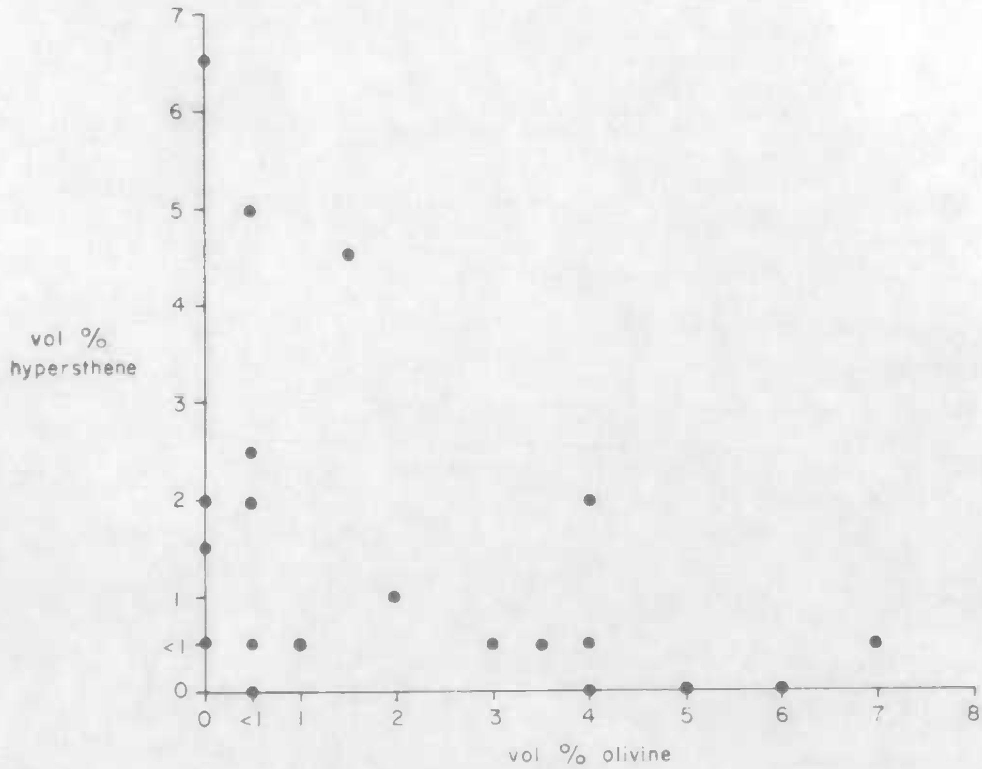

Figure 11: Inverse relationship between volume percentages of hypersthene and olivine phenocrysts (Table 1).

Figure 12: Olivine phenocryst (a) with zones of iron-titanium oxide (b), and pigeonite (c); magnification x 140.

To accompany Record 1970/21

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Iron-titanium oxide phenocrysts are present in some of the rocks, but they are everywhere less than 1% by volume. They are totally absent from all the rocks of group 4. In many cases, the opaque grains are enclosed in silicate phenocrysts or aggregates of phenocrysts.

Groundmass mineralogy. The crystallinity of the groundmass of the samples is variable. It ranges from cryptocrystalline to a coarse-grained matrix in which most of the mineral phases can be identified. Plagioclase laths, grains of iron-titanium oxides, and glass, are found in all the rocks, although, in the coarsely crystalline varieties, glass is only a minor interstitial constituent, and iron-titanium oxides are less well developed.

Owing to the fineness of grain, identification of the groundmass pyroxene is not always possible. However, in the coarser-grained rocks, the most common pyroxenes are the monoclinic varieties, augite and pigeonite. Hypersthene is present in some of the rocks, but it appears to be much less common (groundmass hypersthene is particularly abundant in specimen 0094).

Chemical analyses of four Ulawun rocks are presented in Table 3. Taking the upper SiO_2 percentage limit of basic rocks to be 53 (see, for example, Kuno, 1969), these rocks are basalts; and, as their total-alkali content is low, they are of tholeiitic type. In a total-alkalies vs. silica plot, all four rocks fall in the Hawaiian tholeiite basalt field of MacDonald and Katsura (1964).

An outstanding feature of the analyses is the high percentage of Al_2O_3. This is illustrated on an Al_2O_3 vs. total-alkalies diagram where the four rocks plot at the edge of the "high-alumina basalt" field defined by Kuno (1960). The Ulawun rocks are very similar, both in chemistry and mineralogy, to alumina-rich basalts (with abundant plagioclase phenocrysts) from various parts of Japan (Kuno 1950, 1960; Katsui, 1961).

High alumina contents are characteristic of basalts from the active margins of continents (Green and Poldervaart, 1955; Chayes, 1965). The Ulawun rocks also have TiO_2 percentages less than 1.75% which, according to Chayes (op. cit.) is a further characteristic of "circumoceanic" (as opposed to "oceanic") basalts.

TABLE 1.

MODAL ANALYSES OF 32 ROCKS FROM ULAWUN VOLCANO

Sample number (prefix: 51NG)	Volume % Phenocrysts						
	Plagio-clase	Olivine	Hypers-thene	Augite	Pigeonite	Fe/Ti oxides	Total% Pheno-crysts
0080B	37	<1	<1	<1	<1	<1	37
0079	18	<1(b)	<1	<1	<1	<1	18
0065B*	7	<1(b)	<1	<1	<1	<1	7
0066*	16	<1(b)	<1	1	<1	<1	17
0067*	16	<1(b)	<1	<1	<1	-	16
0076B*	20	3	<1	5	<1	<1	28
0077	19	1.5(b)	4.5	5	ca.1	-	31
0069D*	ca.10(a)	-	-	<1	-	-	ca.10
0071	25	-	2	1	<1	-	28
0094	16	<1(b)	2.5(c)	<1	-	<1	18.5
0093	13	4	2	5	ca.3	-	27
0099	17	<1	5	4	<1	-	26
0150	21	<1	2	4	<1	-	27
0151	33	4	-	2	1	-	40
0098	33	5	-	2	ca.2	-	42
0155	31	6	-	1	<1	-	38
0156	26	2(b)	1	<1	-	-	29
0160	35	4	-	<1	1	-	40
0161	32	4	-	1	ca.1	-	37
0162	31	4	-	2	1	-	38
0157	24	7	<1	3	1	-	35
0158	24	3.5	<1	1.5	ca.1	-	30
0096*	16	<1(b)	-	<1	-	-	16
0059*	7	<1	-	1	<1	-	8
0063*	11	1	<1	1	<1	<1	13
0089*	14	3(b)	<1	4	<1	<1	21
0090	18	4(b)	<1	5	<1	-	27
0091	13	<1(b)	<1	2	<1	<1	15
0095	40	-	6.5	3.5	<1	<1	50
0822	35	-	1.5	1.5	-	-	38
0823	38	-	-	-	-	-	38
0826	41	-	<1	-	-	-	41

* Rocks with a fine-grained groundmass

a. Approximate visual estimate

b. Most olivine phenocrysts rimmed by iron-titanium oxide grains; pseudomorphs of iron-titanium oxides after olivine may also be present; these oxides are included in the olivine phenocryst percentage.

c. Value includes all hypersthene laths down to about 0.25mm. in length, many of which could be considered as groundmass grains.

TABLE 2.

LOCALITY INDEX FOR 32 SAMPLES OF TABLE 1

Group	Sample	Locality
1. Western Valley Stream section (in stratigraphic order)	0080B	800m. a.s.l.; from lower 30cm. of 1-1.3m. thick flow.
	0079	810m. a.s.l.; centre of flow, possibly a sill, 4m.+thick.
	0065B	920m. a.s.l.; centre of 30cm. thick, steeply-dipping flow.
	0066	970m. a.s.l; flow.
	0067	ca. 1050m. a.s.l.; 30-50cm. thick, steeply-dipping flow.
	0076B	boulder in stream bed.
	0077	boulder in stream bed.
2. Northern side of Western Valley.	0069D	ca. 1180m. a.s.l.; talus block beneath lava exposure.
	0071	1380m. a.s.l.; flow.
	0094	910m. a.s.l.; flow.
3. Isolated outcrop on southeastern flank	0093	ca. 1430m. flow.
4. Northwestern Valley stream section. (in stratigraphic order).	0099	360m. a.s.l.; from lower half of 1-1.3m thick flow.
	0150	360m. a.s.l.; top of flow overlying 0099.
	0151	460m. a.s.l.; flow of uncertain thickness.
	0098	570m. a.s.l.; flow of uncertain thickness.
	0155	690m. a.s.l.; flow of uncertain thickness
	0156	710m. a.s.l.; flow of uncertain thickness.
	0160	740m. a.s.l.; centre of 3m. thick flow.
	0161	750m. a.s.l.; from base of 1-1.3m. thick flow.
	0162	760m. a.s.l.; flow of uncertain thickness.
	0157	880m. a.s.l.; flow in gully on north side of main stream
	0158	980m. a.s.l.; 25cm. thick flow in gully on north side of main stream.

(continued)

TABLE 2 (cont'd)

Group	Sample	Locality
5. Younger cone	0096	1200m. a.s.l.; surface flow on southside of Northwestern Valley.
	0059	2130m. a.s.l.; core of bomb on western rim of summit crater.
	0063	2070m. a.s.l.; block at bottom of summit crater.
	0089 0090	1930m. a.s.l.; bombs on south western slopes of Younger Cone.
	0091	1840m. a.s.l.; from base of 8m.t thick flow on southwestern slopes.
	0095	1350m. a.s.l.; bomb on western slopes.
6. Flank fissure lava flow, near Ulamona Mission	0822	1 Km. southeast of mission.
	0823	behind mission schoolhouse.
	0826	coastal exposure 1 Km. west of mission.

TABLE 3.

CHEMICAL ANALYSES OF FOUR ROCKS FROM ULAWUN VOLCANO

	1 67/71/1201	2 51NG 0079	3 51NG 0089	4 51NG 0098
SiO_2	51.1	52.47	52.10	51.79
TiO_2	0.92	0.75	0.75	0.74
Al_2O_3	17.5	19.16	16.78	18.06
Fe_2O_3	4.30	3.40	3.07	2.51
FeO	6.35	5.82	7.32	7.25
MnO	0.13	0.17	0.19	0.17
MgO	5.85	4.90	6.52	5.85
CaO	10.8	10.76	10.84	10.98
Na_2O	2.40	2.45	2.19	2.19
K_2O	0.30	0.32	0.32	0.32
P_2O_5	0.07	0.09	0.09	0.09
H_2O+	0.07	0.14	0.08	0.17
H_2O-	0.23	0.03	0.03	0.06
CO_2	0.13	0.05	0.11	0.08
TOTAL	100.15	100.51	100.39	100.26

1. Ash deposited on Lolobau Island during the January, 1967, eruption of Ulawun. Analyst: A. Jorgensen, Australian Mineral Development Laboratories, Adelaide; analysis by classical methods.

2 - 4 For localities, see Table 2. Analyst: A.J.R. White, A.N.U.; analysis by X-ray fluorescence; FeO, H_2O and CO_2 by classical methods.

REFERENCES

BLAKE, D.H., and MIEZITIS, Y., 1967. -Geology of Bougainville and Buka Islands, New Guinea. Bur. Min. Resour. Aust. Bull., 93.

CURTIS, G.H., 1954 - Mode of origin of pyroclastic debris in the Mehrten Formation of the Sierra Nevada. Univ. Calif. Publ. Bull. Dep. Geol. Sci. V.29, 453-502.

CHAYES, F., 1965 - Titania and alumina content of oceanic and circum-oceanic basalt. Mineralog. Mag., V.34, p.126-131.

DEER, W.A., HOWIE, R.A., & ZUSSMAN, J., 1963 - Rock-forming minerals V.2 (Chain silicates). London (Longmans, Green & Co.) 1st Edn.

DREVER, H.I., and JOHNSTON, R., 1957 - Crystal growth of forsteritic olivine in magmas and melts. Trans. R. Soc. Edin. V.63, p.289-314

FISHER, N.H., 1937 - Geological report on an ascent of the Father Volcano, New Britain. Unpublished report, Geol. Surv. Terr. N. Guinea.

FISHER, N.H., 1939a - Geology and volcanology of Blanche Bay and the surrounding area, New Britain. Geol. Bull. N. Guinea. 1.

FISHER, N.H., 1939b - Report on the volcanoes of the Territory of New Guinea. Geol. Bull. N. Guinea. 2.

FISHER, N.H., 1940 - The volcanoes of the Mandated Territory of New Guinea. 6th Pac. Sci. Congr., Proc. V.2, p.889-894.

FISHER, N.H., 1957 - Catalogue of the active volcanoes of the world including solfatara fields. Part V. Melanesia, Int. Volc. Assoc., Naples.

GREEN, J., & POLDERVAART, 1955 - Some basaltic provinces, Geochim. Cosmoch. Acta. V.7, p.177-188.

KATSUI, Y., 1961 - Petrochemistry of the Quaternary volcanic rocks of Hokkaido and surrounding areas. Hokkaido Univ. Jour. Fac. Sci. V.11, p.1-58.

KRUMBEIN, W.C., and SLOSS, L.L., 1963 - Stratigraphy and sedimentation. (2nd Edn.) San Fransisco and London (W.H. Freeman & Co.).

KUNO, H., 1950 - Petrology of Hakone volcano and the adjacent areas, Japan. Bull. geol. Soc. Amer., V.61, p.957-1020.

KUNO, H., 1960 - High-alumina basalt. J. Petrology, V.1, p.121-145.

KUNO, H., 1969 - Andesite in time and space. Bull. State of Oregon, Dept. Geol. Mineral Industries, v. 65, p.13-20.

MACDONALD, G.A., 1968 - A contribution to the petrology of Tutuila, America Samoa. Geol. Rundschau, V.57, p.821-837.

MACDONALD & KATSURA, T., 1964 - Chemical composition of Hawaiian lavas. J. Petrology, V.5, p.82-133.

McCALL, G.J.H., 1957 - Geology and groundwater conditions in the Nakura area. Tech. Rep. hydraul. Brch Minist. Wks Kenya., 3.

MUIR, I.D., & LONG, J.V.P., 1965 - Pyroxene relations in two Hawaiian hypersthene-bearing basalts. Mineralog. Mag., V.34, p.358-369.

SMITH, R.L., and BAILEY, R.A., 1969 - Resurgent Cauldrons. In Mem. geol. Soc. Amer. v. 116, p. 613-662.

STICE, G.D., 1968 - Petrography of the Manula Islands, Samoa Contr. Mineral. Petrol., V.19, p.343-357.

TAYLOR, G.A.M., 1958 - Notes on the current eruption at Manam. Bur. Min. Resour. Aust. Rec. 1958/67 (unpubl.).

UPTON, B.G.J. and WADSWORTH, W.J., 1965 - Geology of Reunion Island, Indian Ocean. Nature, v. 207, p. 151-154.

WILLIAMS, H., 1941 - Calderas and their origin. Univ. Calif. Publ. Bull. Dep. geol. Sci., v. 25, p. 239-346.

APPENDIX A

Air-photograph index of the Ulawun area

1. U.S. Army Map service; supplied by Division of National Mapping, Canberra; all photographs taken at 23,500' above sea-level.

    Mission 582 (June 17, 1948); run 53, nos. 36-40
    run 54, nos. 24-28
    Mission 197 (November 17, 1947); run 55, nos. 120-124.

2. QASCO Series, "Central New Britain"; all photographs taken at 15,000' above sea-level:

    CAJ5002 (July 21, 1965); run 2, nos. 5055-5063
    CAJ5005 (August 15, 1965); run 3, nos. 5064-5076
    run 4, nos. 5098-5108
    run 5, nos. 5140-5150

APPENDIX B

Discussion on the origin of zones of iron-titanium oxide and pigeonite at the peripheries of olivine phenocrysts

Olivine phenocrysts in many of the Ulawun lavas are rimmed by zones of iron-titanium oxides, or pigeonite, or both. In this Appendix, these features are described and discussed in detail.

Magnesian olivine, mantled by aggregates of Ca-poor pyroxene (pigeonite, hypersthene, or enstatite), is a diagnostic feature of tholeiite basalts in which the Ca-poor pyroxene is generally interpreted as being produced by crystallisation from a liquid, at the expense of olivine, which is resorbed as cooling and crystallisation proceed. The olivine is said to bear a "reaction relationship" with Ca-poor pyroxene (MacDonald and Katsura, 1964).

On the other hand, there are two conflicting theories for the origin of the iron-titanium oxides. One concept is that the opaque oxides - and the Ca-poor pyroxenes associated with them - are the result of high temperatures oxidation of olivine (Muir, Tilley, and Scoon, 1957; Yoder and Tilley, 1962; Haggerty and Baker, 1967). The other is that the oxides are an additional product of a "reaction relationship" involving liquid, olivine, and Ca-poor pyroxene (Kuno, 1950; Presnall, 1966). One of the purposes of this Appendix is to discuss which of these interpretations best explains the features in the Ulawun rocks.

In those Ulawun rocks with no oxide zones to the olivine phenocrysts, pigeonite rims are best developed on phenocryst olivine enclosed in a coarse, crystalline groundmass: in rapidly chilled rocks, the pyroxene sheath is either poorly developed or absent. This indicates that the development of pigeonite in these cases is a function of the rate of cooling of the lava, and that the pigeonite crystallised from a liquid.

In contrast, the development of iron-titanium oxide zones around phenocryst olivine (with, or without, an accompanying pyroxene zone) does not depend upon the rate of cooling, as these are found in rocks with both rapidly-chilled, and coarse, crystalline groundmasses. Neither does their development appear to depend upon the bulk composition of the rock, as the iron-titanium oxides are developed in samples that show a considerable range in the percentage and type of phenocryst (see Table 1).

Figure 12 illustrates the relationships commonly observed in an olivine phenocryst that exhibits rims of both iron-titanium oxide and pigeonite. The iron-titanium oxides occupy a zone between the pigeonite rim and the olivine core. In many examples, this zone is discontinuous: some olivine crystal faces are crowded with oxides, but other faces on the same crystal are completely clear. Charactistically, the oxides concentrate at the corners of the olivine grains. This contrasts with the pigeonite zones which are continuous, and of more or less uniform thickness, their outer edges paralleling the outline of the olivine crystal. In most rocks with a fine-grained groundmass and containing phenocryst olivine with oxide rims, the pigeonite zones are poorly developed, and, in many cases, they are barely resolved by the microscope; in some rocks they appear to be absent.

In thin sections of normal thickness (about 30 microns), the iron-titanium oxide zones of many olivine phenocrysts are completely opaque. This is almost certainly due to overlap of opaque grains within the rock section, and it is probable that silicate minerals (olivine or pyroxene, or both) are present as interstitial phases. At the inner edge of the oxide zone, the opaque grains show symplectic growths into olivine. At the outer edge of the oxide zone, symplectic growths into pyroxene are present, but they are poorly developed in comparison to those at the interface with olivine.

Several rocks show olivine phenocrysts that appear to be completely replaced by iron-titanium oxides: every stage may be observed between olivines with narrow oxide rims and complete pseudomorphs of oxides after olivine. Isolated areas of oxides within olivine crystals are rare, and the general rule appears to be that oxides first replace olivines at the outside, and then extend progressively inwards.

These textures indicate that the development of the iron-titanium oxides in the olivine phenocrysts is a solid-state replacment phenomenon involving the exchange of oxygen; that is, they are pseudomorphs after olivine. Muir, Tilley, and Scoon (1957) described similar relationships in the olivines of metamorphosed picrite basalts from Hawaii, and described the oxidation reaction by the following (Ca-free) equation:

$$3Fe_2SiO_4 + 3Mg_2SiO_4 + O_2 = 2Fe_3O_4 + 6MgSiO_3$$

olivine　　　　　　　　magnetite　enstatite

They also considered that this reaction involved "introduction of iron from the environment of the phenocryst olivine, magnesia moving out, and silica likewise if the content of the magnetite is high."

The transformation of olivine to oxides in the Ulawun rocks almost certainly resulted in the formation of magnesium-rich minerals- pigeonite, olivine enriched in MgO, hypersthene, or enstatite. Although these minerals are probably interstitial to the oxide grains, it is also possible that they could have segregated into distinct zones, peripheral to the olivine phenocrysts. However, as concluded previously, the pigeonite rims to the phenocryst olivine with no oxide zones, almost certainly originated by crystallization from a liquid with which olivine was reacting. Thus, the peripheral zones of pigeonite may have originated by either, or both, of two processes: high temperature oxidation, and reaction of olivine with liquid.

On the other hand, the iron-titanium oxide zones appear to have been the products of oxidation alone. They were not involved in a liquid-crystal reaction relationship, as proposed by Kuno (1950) and Presnall (1966), as they pseudomorph phenocryst olivine in rocks with either coarsely crystalline or fine-grained matrices; that is, their appearance is not a function of the rate of cooling. Instead, their development is most probably due to a high oxidation state in the lavas, and the solid-state breakdown of olivine.

REFERENCES

HAGGERTY, S.E., & BAKER, I., 1967 - The alteration of olivine in basaltic and associated lavas. Part 1. High temperature alteration. Contr. Mineral. and Petrol., V.16, p.233-257.

KUNO, H., 1950 - Petrology of Hakone volcano and the adjacent areas, Japan. Bull. geol. Soc. Amer., V.61, p.957-1020.

MACDONALD, G.A., & KATSURA, T., 1964 - Chemical composition of Hawaiian lavas. J. Petrology, V.5, p.82-133.

MUIR, I.D., TILLEY, C.E., & SCOON, J.H., 1957 - Petrology of Hawaiian basalts. Part 1. The picrite-basalts of Kilauea. Amer. J. Sci. V.264, p.241-253.

PRESNALL, D.C., 1966 - The join forsterite-diopside-iron oxide and its bearing on the crystallisation of basaltic and ultramafic magmas. Amer. J. Sci., V.264, p.753-809.

YODER, H.S. Jr & TILLEY, C.E., 1962 - Origin of basaltic magmas: an experimental study of natural and synthetic rock systems. J. Petrology, V.3, p.342-532.