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Record 1971/55

BAMUS VOLCANO, LAKE HARGY AREA, AND SULU RANGE, NEW BRITAIN: VOLCANIC GEOLOGY AND PETROLOGY

by

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SUMMARY

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Bamus, or South Son, is a symmetrical stratovolcano, similar in size, form, and structure to Ulawun volcano (Johnson, 1970a). A well-defined north-south lineament - probably a fault - extends across the western flank of Bamus, and a well-preserved crater is present at the summit of the volcano. A tholoid, which occupies the summit crater, was probably formed at the same time as a nuée ardente was erupted down the southern flank. This eruption probably took place within the last hundred years, and as solfataras are also present at the summit, Bamus is considered to be potentially active. The lavas of Bamus are all andesites. Almost all of them contain phenocrysts of plagioclase, pleochroic orthopyroxene, and augite; olivine and iron-titanium oxide phenocrysts are present in some samples.

Hargy caldera occupies the summit of an old volcano which was probably similar in size to Bamus and Ulawun volcanoes. The caldera is about 13 km across. Lake Hargy occupies the southern part of the caldera, and Galloseulo has grown in the western part, some of its lavas mantling the caldera rim in the west. Thermal activity is present in the summit crater of Galloseulo. A "remnant block" in the eastern part of the caldera is probably part of the central portion of the original Hargy volcano, which wedged between the caldera wall and the remainder of the subsiding cauldron block. The lavas of the Lake Hargy area range from olivine-bearing types to dacites; lavas of andesitic compositions, containing phenocrysts of plagioclase, pleochroic orthopyroxene, and augite, are common.

Sulu Range is a cluster of coalescent volcanic cones. The highest cone is Ruckenberg, which rises about 550 m above sea-level, and which has a crater at its summit. The lavas of Sulu Range show a wide range of compositions - from olivine-bearing basalts, to rocks of intermediate composition (with phenocrysts of plagioclase, pleochroic orthopyroxene, and augite), to rhyolites that contain abundant quartz phenocrysts and some amphibole phenocrysts.

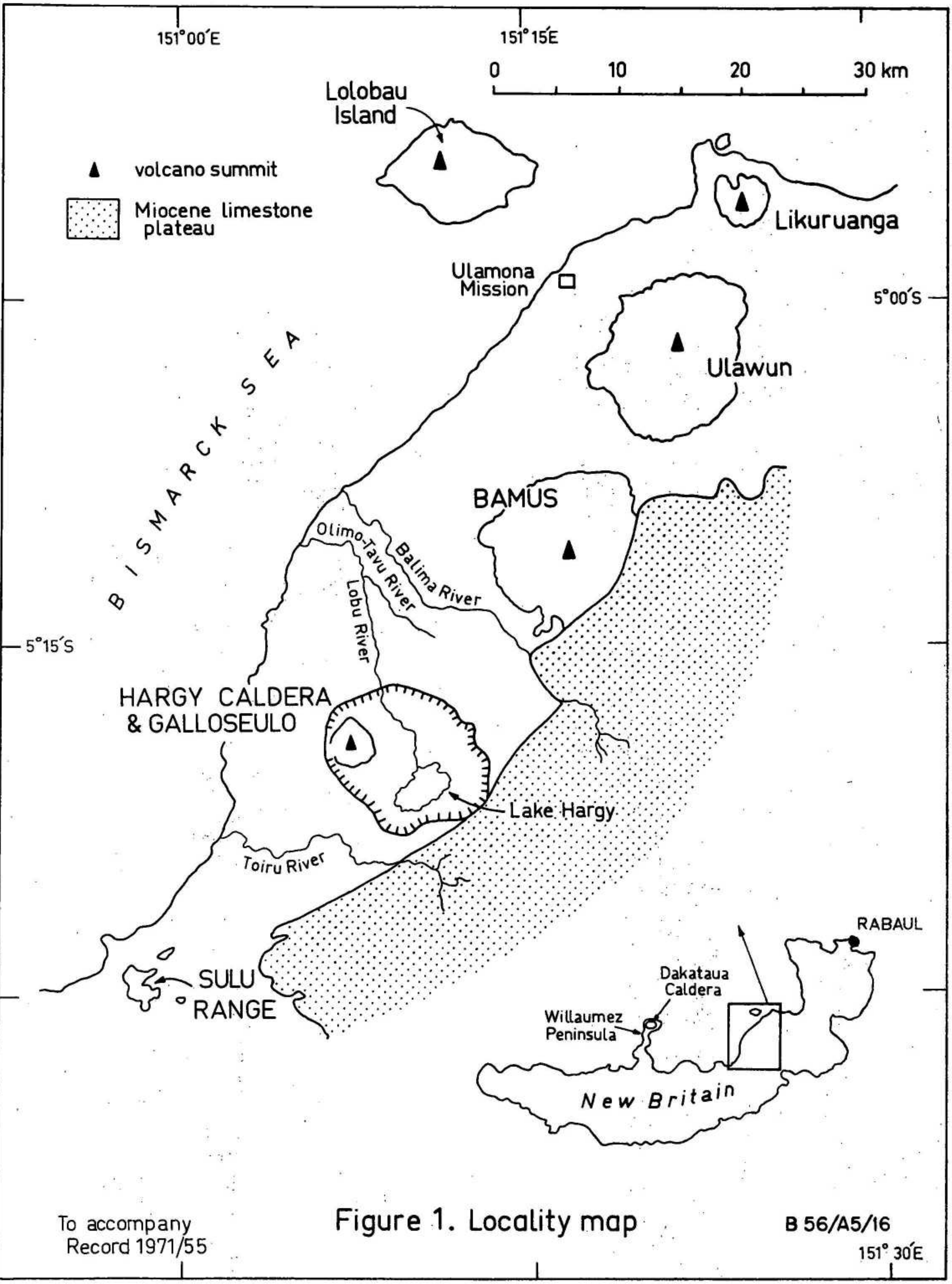

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Figure 1. Locality map

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INTRODUCTION

The three major Quaternary volcanic centres described in this Record constitute the southwestern half of a line of volcanoes along the northwestern coast of eastern New Britain (figure 1). These three centres are:

(1) Bamus volcano,

(2) Hargy caldera, within which Galloseulo volcano has grown,

(3) Sulu Range, a cluster of volcanic cones.

This Record describes the geology and petrology of the three centres. It is the fifth in a series of geological reports on the Quaternary volcanoes of New Britain (see Johnson, 1970a,b; Johnson, Mackenzie, and Smith, 1970; Johnson, Davies, and Palfreyman, 1971).

The three volcanic centres were examined by R.P. Macnab, R.J. Ryburn, and the writer between 20 September and 6 October, 1969, using m.v. "Explorer" as a mobile base camp. In addition, the writer spent five days in the Lake Hargy area in April, 1969; a Bell "Jetranger" helicopter was used for positioning and pick-up of the traverse party. Two-hundred-and-six samples collected from the three volcanic centres have been examined in thin section by the writer.

BAMUS VOLCANO

Topography and General Geology

Bamus, or South Son, is a symmetrical stratovolcano similar in size, form, and structure to Ulawun, the active volcano 20 km to the northeast (figures 1 and 3). Bamus and Ulawun dominate the scene along this part of the New Britain coastline, and they tower above the volcanic centres of Lolobau Island and Likuruanga volcano, in the north, and Galloseulo volcano and Sulu Range, in the south (figure 3).

Bamus is slightly lower than Ulawun: on the U.S. Army 4" to 1 mile map of Central New Britain, the altitude of Bamus is given as

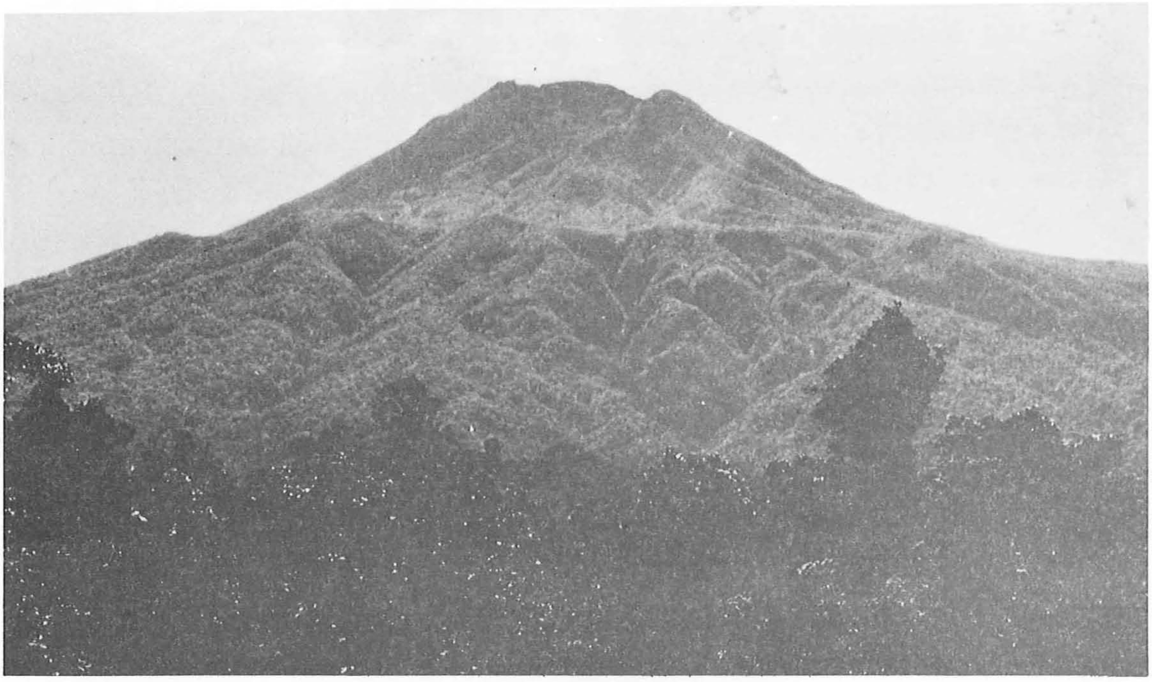

Figure 2. Western flank of Bamus volcano from near Gigipuna village, showing summit crater and tholoid, and the benchline half way up the mountain that marks the trace of the north-south lineament. Neg. GA/3011

7376' (2248 m) which is 92 m less than the height reported by Davies (1970) for Ulawun. At the 200 m contour level, Bamus is 16 km wide in a northeast-southwest direction; this compares with 18 km for the same parameter on Ulawun (Johnson, 1970a).

The southeastern flank of Bamus merges with a limestone plateau (dated as Miocene by Binnekamp, 1971) to the east (figures 1 and 3). The northwestern flank flattens off at sea-level, and the northeastern and southwestern slopes form saddles with the lower flanks of Ulawun and Hargy volcanoes respectively. About half way up the western flank of Bamus a well-defined lineament trends north-south. West of this lineament the flanks reach a maximum slope of about 20°. Immediately to the east of it, the slopes of the volcano are a few degrees, but they increase to about 34° immediately below the summit of the mountain. Rainforest mantles almost the entire volcano, but on the steep slopes, close to the summit, forest gives way to thicket. The summit area is mainly covered by grasses and bracken, and a tholoid which occupies a summit crater is more or less bare of vegetation.

The structure of Bamus closely resembles that of Ulawun: lava flows and pyroclastic materials, erupted mainly from a central vent, have built a symmetrical, conical stratovolcano. Collapse of the summit region of Bamus gave rise to the north-south lineament (probably a fault) on the western flank, and subsequent eruptions from a central vent built the volcano to its present height. Probably the last major volcanic activity was the extrusion of the tholoid into the summit crater. Deposits of a nuée ardente on the southern flanks of Bamus may have been emplaced at the time the summit tholoid was extruded. Satellite eruptive centres on the outer slopes of Bamus also produced cones and craters.

None of the eruptions reported from Bamus this century has been confirmed by volcanologists, but as there is solfataric activity in the summit crater the volcano is considered to be potentially active (Fisher, 1957). The village of Gigipuna, 8 km inland from Soi Logging Camp, and above the northern bank of the Balima River, is the closest observation point to the summit crater, 11 km to the east (figure 3). The summit is also visible from points on the coastline close to Ulamona Mission 23 km to the north (figure 1), and from many other points along the coast to the west.

Geological Investigations

Short geological accounts of Bamus were given by Fisher (1939b, 1940, 1957) who, with L.C. Noakes, climbed to the summit crater in October, 1937. Fisher (1942) also reviewed the economic potential of sulphur deposits in the summit area. J.G. Best, a former volcanologist at the Central Volcanological Observatory, Rabaul, climbed Bamus between October 17 and 20 1951, and recorded aspects of his ascent in an unfinished, hand-written report (in File VF/9A, Central Volcanological Observatory). G.W. D'Addario made a helicopter landing on the summit of Bamus on 1 May, 1965; he camped overnight, and was picked up by helicopter the following day (report on solfatara deposits in May Monthly Report 1965, Central Volcanological Observatory).

R.P. Macnab, R.J. Ryburn, and the writer examined Bamus volcano between September 20 and October 2, 1969. The survey consisted of an ascent of the volcano to the summit crater by Macnab and Johnson (20-25 September), a traverse along the Balima River by Ryburn (20-25 September), and a traverse by Macnab along the Bia River on the western flank of Bamus (1-2 October).

Early volcano

The older parts of Bamus are exposed on the western flank and in the Balima River valley. On the western flank, lava flows and interbedded layers of clastic deposits dip at angles of up to about 20°, more or less parallel with the slope of the mountain side. In places, the clastic layers are thick (up to 15 m) and unsorted, suggesting they could have been emplaced by nuées ardentes.

Exposures along the Balima River show lavas from Bamus overlying Miocene limestone. These flows display vertical columnar jointing and well developed, closely-spaced horizontal joint planes, and they are interpreted as lavas which ponded in an old stream valley (figure 8).

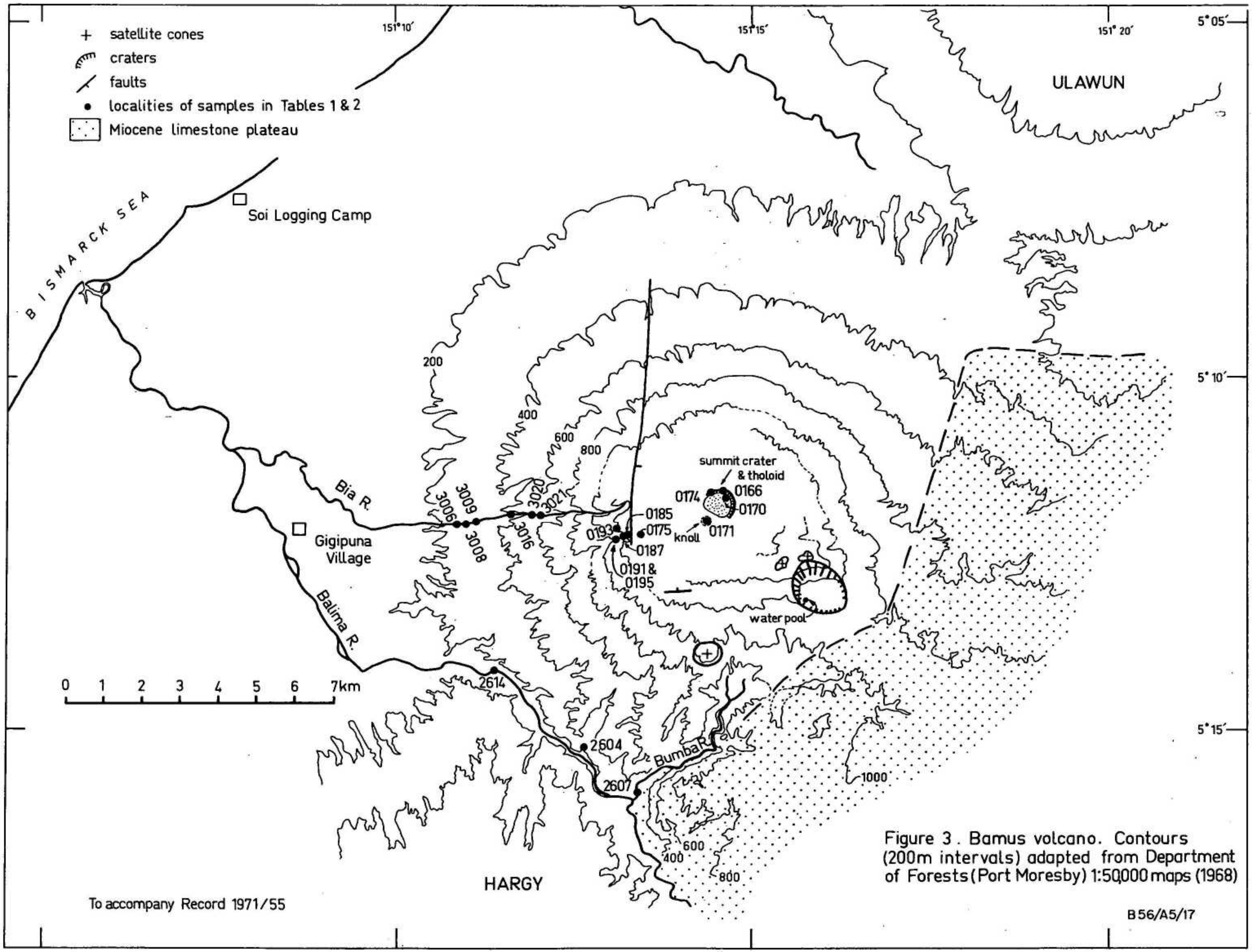

Figure 3. Bamus volcano. Contours (200m intervals) adapted from Department of Forests (Port Moresby) 1:50,000 maps (1968)

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On aerial photographs (figure 4), a north-south lineament, about 7 km long, is clearly shown on the western flank of Bamus. The lineament shows as a prominent cusp in the profile of the volcano when viewed from the north, and from the west it appears as a horizontal benchline slightly more than half way up the mountain side (figure 2). The lineament can be traced northwards, without change in trend, to the lower flanks of Bamus, cutting across the direction of drainage (figure 3). A second linear feature - a northward-facing escarpment about 750 m long - is also present on the southwestern flank of Bamus (figure 3).

The north-south lineament on Bamus is similar to the prominent east-west escarpment on Ulawun volcano (Johnson, 1970a). The origin of the Ulawun escarpment was discussed at length (Johnson op. cit.), and it was concluded the scarp represented either part of a linear graben straddling the volcano, or was the remnant of a caldera modified by erosion. The same interpretation may be given to the linear features on Bamus. It is possible the north-south lineament, and the short escarpment on the southwestern flank, are the remnants of an old caldera that was severely modified by erosion, and that the northern, eastern, and southeastern parts of the caldera were mantled by later volcanic products**. However, the lineament is straight and cuts across the drainage, suggesting it is probably a linear fault. This fault could be part of a graben, the remainder of which has either been removed by erosion or mantled by later volcanic products. Alternatively, the fault may be a major fracture along which the entire eastern part of the volcano subsided.

At its time of formation, the north-south fault almost certainly formed a high eastward-facing escarpment. When volcanic products continued to be erupted from a central vent in the east, they produced a cone whose western margin was buttressed against the fault. Some lavas probably spilled over the escarpment and flowed down the flanks of the older part of the volcano.

** Fisher (1957) stated that "on both the western and eastern sides of the mountain at an elevation of about 1000 m remnants of an older caldera can be seen". The western remnants are equivalent to the north-south lineament of this account, but the eastern "remnants" are interpreted as an area of satellitic volcanic activity (see next section).

Immediately east of the fault, horizontal beds of clastic materials intercalated with lava flows are exposed in deep valleys. These deposits show graded bedding, and "flame" structures caused by load compaction. Fine bedding extends up to, but does not mantle or dip beneath large clasts, indicating that the material was emplaced by fluvial processes; no impact structures are present beneath the larger clasts. These bedded deposits could have been deposited in a lake impounded by the fault, but it is believed more likely that they represent outwash material trapped against the former escarpment.

On the aerial photographs, pronounced differences in depth of erosion are shown between the slopes west of the north-south fault, and those to the east (figure 4). Deep precipitous gorges have been cut into the western part of the cone, exposing the outward-dipping lava flows and clastic rocks. At the fault, the gorges terminate in steep cliffs, to the east of which the younger part of the volcano is not so deeply dissected. This difference in erosion is almost certainly due to the difference in age between the two parts of the volcano. However, it is possible that another contributory factor is the presence east of the fault of thicker, flat-lying lava flows which were ponded against the escarpment, and which are more resistant to erosion than the thinner, outward dipping lava flows on the outer flanks.

South of Gigipuna village, about 50 m of flat-lying volcanic sediments are exposed in the northern bank of the Balima River. The sediments are well-bedded, semi-consolidated, and deeply weathered. Constituent fragments are less than about 3 cm in diameter. Some of the larger fragments are light-coloured, and easily crumble between the fingers, suggesting they may originally have been pumice. Exposures of these sediments have not been found elsewhere along the Balima River. The source and origin of the sediments is uncertain, but it is thought they probably represent water-laid volcanic deposits which form a basement to Bamus volcano.

Summit area, and satellite cones and craters

The summit of Bamus is occupied by a crater about 800 m wide, which is breached on its western and southern sides (figure 5). The

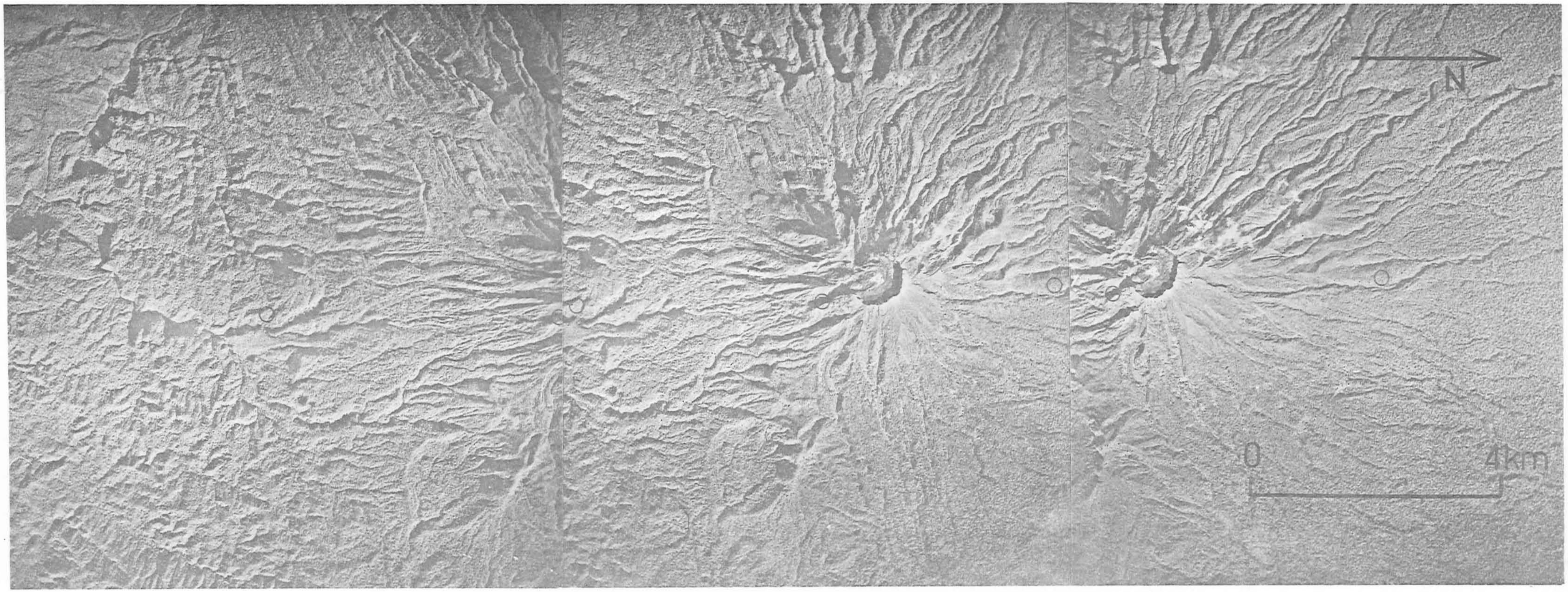

Figure 4. Stereoscopic pairs of aerial photographs showing summit area of Bamus volcano. (Taken 17/6/48).

precipitous crater walls are about 60 m high, and they expose excellent sections through several lava flows and underlying agglomerate.

The lavas are exposed in the upper parts of the crater wall. They are revealed as thick flows which appear to thin out downslope producing the dip slopes of the flanks outside the crater (figure 6). At the thickest parts of the flows, the upper surfaces produce high points in the crater rim and, in at least one place, there is a suggestion that feeder plugs or dykes are present beneath them. The interiors of the flows are homogeneous and non-vesicular, and show crude columnar jointing. A coulée or cumulodome forms a prominent knoll a few hundred metres southwest of the summit crater (figure 3): it is well-exposed in cross-section on its northern side where the upward-flaring joint pattern suggests that a feeder vent is exposed beneath the flow (figure 7). In thin section, the groundmass of samples from the interiors of flows are seen to be fine-grained; this feature is ascribed to the high viscosity of these lavas which has inhibited crystal growth.

Poorly sorted and crudely bedded agglomerate, which in places is thermally altered, is exposed in the lower part of the summit crater wall. Lava blocks over 1 m in diameter are contained in the deposit. The bedding dips into the crater, suggesting the deposit either mantles the inner slope of an old crater or else is banked against it. The agglomerate is not present beneath the thick coulée forming the knoll southwest of the crater; here, instead, a series of well-jointed lava flows is exposed (figure 7).

The summit crater is occupied by a tholoid. This extrusion is a dome-shaped mass, with steep sides flanked by talus, and an upper surface consisting of a jumbled mass of spinose and scoriaceous blocks. The tholoid is highly oxidised, and no unaltered samples were collected. It is buttressed to the north and east by the walls of the summit crater (figure 5), but it extends short distances onto the western and southern flanks of the volcano (figure 6). The absence of vegetation and the youthfulness of its surface structure suggest that the tholoid could have been erupted within the past hundred years.

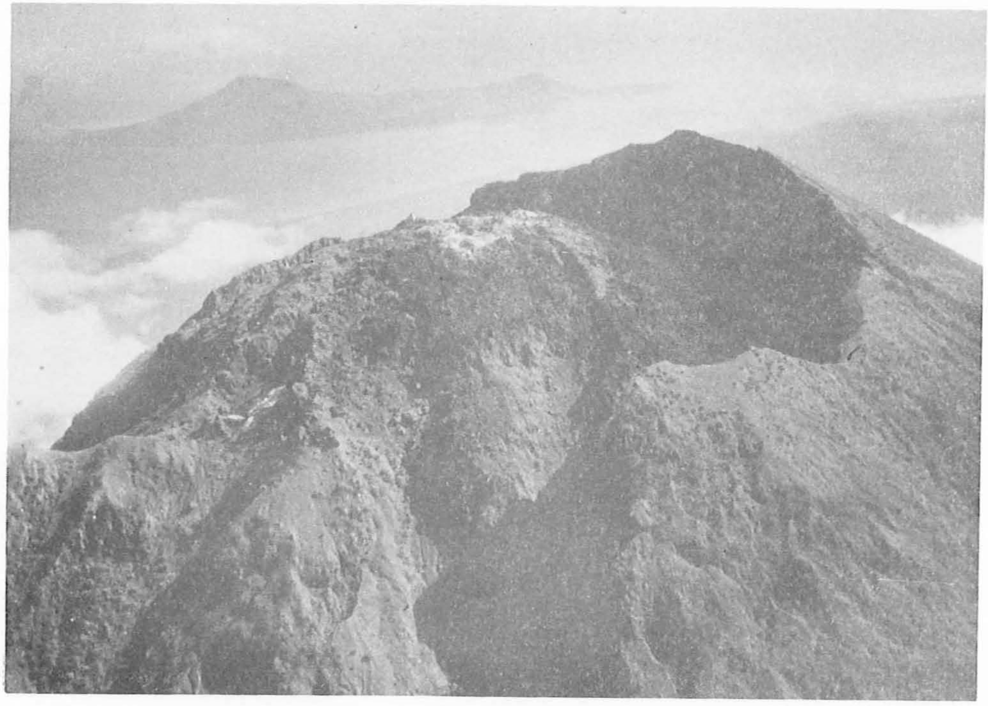

Figure 5. Summit crater of Bamus from south-southeast, showing tholoid and thermal areas (white patches). In the distance is Lolobau Island. Photograph taken by G.W. D'Addario, 1/5/65.
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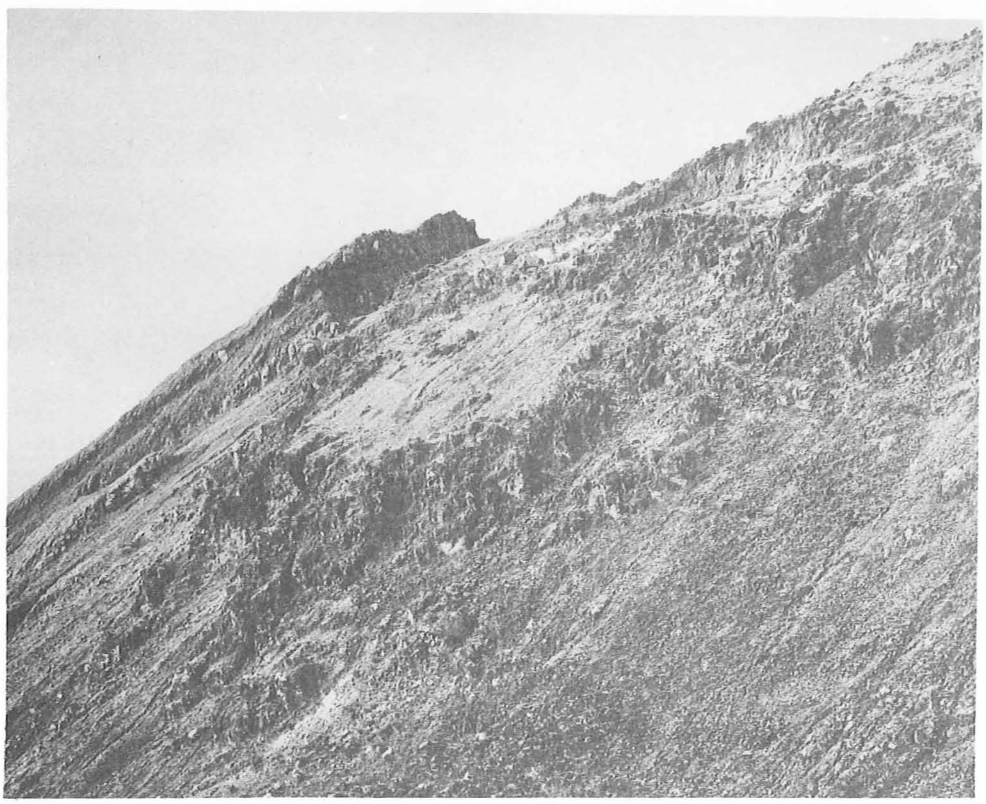

Figure 6. Western edge of tholoid where it overflowed the summit crater rim. Lava flows in the background dip westwards, away from the crater. Neg. M/976.

Two sites of satellite volcanic activity have been identified: one is a timber-covered hill on the southern flank; the other is a prominent crater, about 1500 m wide, halfway up the southeastern flank (figure 3). The floor of the crater dips to the southeast, and a pool of water is present in its western part. Two small peaks, which are probably satellite cones, are present north and northwest of the crater (figure 3). Both peaks appear to be covered by stunted vegetation, and they are possibly the locality from which "several emanations of steam" were observed by Stanley (1922).

Nuee ardente deposit

A clastic deposit, probably emplaced by a nuee ardente, is exposed in Bumba stream, which drains the southern flank of Bamus (figures 3 and 9). The deposit crops out in a 15 m-high terrace about 300 m upstream from the junction of the Bumba stream with the Balima River. The lowest 6 m of the terrace is buried beneath fallen debris, but the upper 9 m reveals a poorly sorted, unstratified, and unwelded deposit of angular to subrounded clasts up to 15 cm, but mainly 3-5 cm in diameter (figure 9). The uppermost 3 m of the outcrop differ from the underlying part in containing numerous lava boulders over 30 cm in diameter. It is also more coherent, and sheds large boulders of volcanic rudite, up to about 4 m in diameter, into the stream below. Many of the clasts in the deposit are light grey and scoriaceous or pumiceous; others are darker and non-scoriaceous, and some are reddish and oxidized. No limestone clasts were observed. Fifteen samples of lava clasts have been examined in thin section, and all are of a similar mineral content to the lava flows on Bamus: they consist of phenocrysts of plagioclase, orthopyroxene, augite, and iron-titanium oxide in a matrix which in all cases is glassy or fine-grained.

The unsorted, unstratified nature of the deposit, and its apparent restriction to the Bumba stream valley, suggest that the clastic material was emplaced by a nuee ardente which swept down the valley from a source at or near the summit of Bamus. Most of the deposit appears to have been destroyed by erosion, but it may also form an undissected terrace about 3.5 km upstream from the outcrop described above.

Figure 7. Northern side of thick coulée or cumulodome (a), southwest of the summit crater of Bamus. Thinner flows (b) which underlie the coulée dip westwards. Neg. M/976.

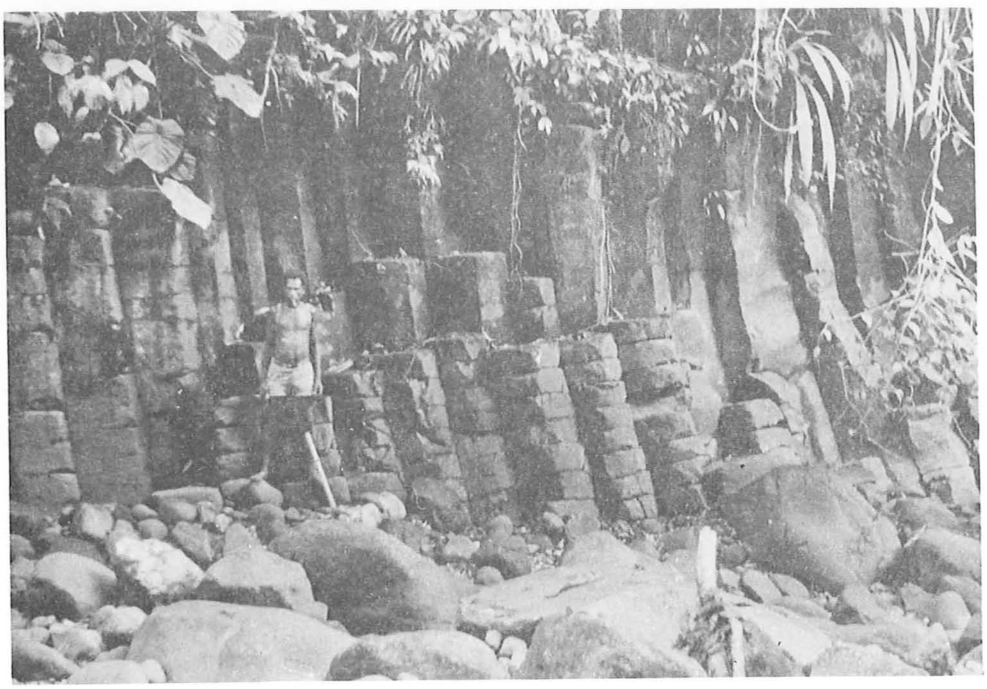

Figure 8. Columnar jointed lava flow in tributary of the Balima River. This flow ponded in a valley cut into limestone. Neg. M/967.

The nuee ardente deposit is almost certainly a product of one of the most recent eruptions from Bamus, and it may have been formed within the last hundred years. Although there have been no confirmed eruptions from Bamus, villagers from Gigipuna tell of an eruption which could account for the geological observations. One villager, probably 40-50 years old, told that his father remembered an eruption taking place in his early childhood; the father died an "old man" during the Second World War, which would date the eruptive event as taking place about 80-100 years ago (1870-1890). The eruption is said to have destroyed vegetation on the western and southern flanks of Bamus (but not at the coast), and to have produced "flows" down the major stream valleys. Before the eruption the summit of Bamus was said to have been a single peak, but after the event the summit had disappeared and a second "peak" had grown in its place. The tholoid may have been emplaced during this eruption. The extrusion of such tholoids is commonly accompanied by the eruption of nuées ardentes - for example, Mont Pelée (Anderson and Flett, 1903) and Mount Lamington (Taylor, 1958) - and it is conceivable that the nuée deposit in the Bumba stream valley was produced from one of the "flows" that moved down the southern flank.

Reports of volcanic activity

Powell (1883) and Stanley (1922) both reported "smoke" and steam emanations when they viewed Bamus. Powell sailed near the volcano and noted that, compared with Ulawun, "... South Son does not eject such a volume of smoke, neither is there apparently any solid substance thrown up with it ...". Stanley also viewed Bamus from the sea, and stated: "... about 3,000' up on the Eastern slopes of the South Son several emanations of steam were noticed. The continual halo of vapour about the apex of the mountain points to the fact that it is in a small way active".

Reports of more recent vapour emissions have been received by the Central Volcanological Observatory in Rabaul. On 27 September, 1951, the Captain of a QANTAS aircraft reported "smoke and steam ... rising from the S.W. side of the South Son (Mount Bamus)". After an unsuccessful attempt to view the volcano from the air on 28 September, 1951, J.G. Best made a ground inspection of Bamus, between 17 and 20 October. He reached the summit crater, but found no evidence of recent volcanic activity. Best believed, however, that a recent landslide had taken place which was thought to account for the emissions reported by the QANTAS pilot (unpublished report on File VF/9A at Central Volcanological Observatory).

Father J. Stamm, who observed the volcanic activity of Ulawun volcano for most of the period between 1915 and 1965, did not recall having seen any activity on Bamus during this period (written personal communication, 1969). He reported, however, that a colleague, Father Reischl, and others from Ulamona Sawmill, had observed volcanic activity from Bamus in January, 1967, at the time Ulawun was in eruption: "... they saw a big cloud, that had just come from the mountain". Brother F. Kleinelanghorst of Ulamona Mission also reported to the Central Volcanological Observatory that there had been activity from Bamus in February, 1967, and he itemised the following observations:

Feb. 13th	Light to medium grey emissions
14th	Light to medium grey emissions
15th	Only a very light white plume
16th	Light to medium grey emissions
17th	Light to medium white grey emissions

Brother Kleinelanghorst added: "Only the activity on the 17th was seen by myself. The other information I received from natives from Inke Village which is about 20 miles S.E. of Mount Ulawun". These reports of activity in 1967 have not been confirmed, and although it is possible that there may have been short-lived volcanic emissions of vapour it seems equally possible that atmospheric clouds could have been mistaken for volcanic emanations.

Although it is doubtful that Bamus has produced an eruption this century, the volcano is nevertheless considered to be potentially active as solfataras are present in the summit crater (Fisher, 1957), and, as mentioned above, geological evidence suggests eruptions have taken place within the last hundred years. In September, 1969, hydrothermal activity was restricted to a small area on the southern part of the tholoid where a few emanations of water vapour, issuing at low pressures, were associated with minor amounts of sulphur (figure 5).

Deposits of extinct hydrothermal areas were also present on other parts of the tholoid and on the crater wall. According to Fisher (1942), who visited the summit crater in 1937, sulphur "usually 3 to 4 inches thick is distributed more or less irregularly over several hectares ... it seems likely that a few hundred tons of sulphur exist here". These quantities of sulphur were not observed in September, 1969, and it is assumed they must have been removed by erosion.

Petrology

The lavas sampled from Bamus volcano, like those of Ulawun (Johnson, 1970a), are of uniform composition: one-hundred-and-four rocks have been examined in thin section, and in all but a few of these the same phenocryst and groundmass minerals are present. Chemical analyses of ten samples, (which will be presented and discussed in detail elsewhere) show silica values of between 53 and 58 percent, indicating andesitic compositions.

The majority of the Bamus lavas contain phenocrysts of plagioclase, orthopyroxene, and augite. In all but a few rocks, plagioclase is the most common phenocryst, and in most of them orthopyroxene is more abundant than augite. Olivine and iron-titanium oxide phenocrysts are present in some of the samples. Modal analyses of twenty-five rocks from Bamus are given in Table 1, and their localities are listed, and divided into five groups, in Table 2.

Plagioclase is the most abundant phenocryst: it comprises between 14 and 37 percent of all but one of the rocks listed in Table 1; sample 3006 is exceptional in containing only 1 percent plagioclase phenocrysts. As in lavas from other volcanoes along the north coast of New Britain (cf. Johnson 1970a,b), many of the plagioclase phenocrysts are zoned (oscillatory and normal zoning are common); furthermore, they commonly contain groundmass and mineral inclusions, and in many cases are clustered in aggregates with, or without, ferromagnesian phenocrysts.

The compositions of twelve plagioclase phenocrysts in five rocks from Bamus, determined by the combined Carlsbad-Albite twin method, fall in the range An64-82 (mainly bytownite).

Clinopyroxene. Augite is present in most rocks, but in more than half of the samples of Table 1 the amount is 1 percent or less. Two rocks contain 6 percent augite, but both samples are unusual in containing high percentages of olivine (17 percent in 2607) and orthopyroxene (12 percent in 3006).

Pleochroic orthopyroxene phenocrysts are present in all but one of the samples examined from Bamus, and in most the amount is more than 1 percent (Table 1). In most rocks, the orthopyroxene phenocrysts are rimmed by narrow selvages of augite.

Magnesian olivine phenocrysts are present in a few samples, but in most of these the amount is less than 1 percent. Olivine appears to be present as phenocrysts in lavas that also contain phenocrysts of iron-titanium oxide. The lavas of group 3 (Table 2) and flows from the lower part of the Bia River section (part of group 2), are conspicuously deficient in olivine phenocrysts. Sample 2607, on the other hand, is exceptional in containing 17 percent olivine phenocrysts.

In some rocks, fresh olivine phenocrysts are rimmed by grains of orthopyroxene. This contrasts with the olivine-bearing rocks from Ulawun volcano (Johnson, 1970a) in which the phenocryst olivine is rimmed by fine-grained clinopyroxene (pigeonite). In both cases, however, the pyroxene rims indicate that the rocks are silica-saturated (tholeiitic) and that the olivine bears a "reaction relationship" with calcium-poor pyroxene (MacDonald and Katsura, 1964).

In a few rocks, the olivine phenocrysts are rimmed by iron-titanium oxides, and in others they are replaced by "iddingsite". As in the case of olivine-bearing rocks from Likuruanga volcano and Lolobau Island (Johnson, 1970b), no pyroxene coronas are found on the iddingsitized olivine grains, indicating that alteration to iddingsite may have taken place before the olivine had opportunity to react with liquid to form calcium-poor pyroxene.

Iron-titanium oxide phenocrysts are present in many of the Bamus rocks, but rarely in amounts greater than 1 percent. A striking feature of the Bamus lavas is the manner in which some sequences of lavas contain iron-titanium oxide phenocrysts, whereas others do not. For example, all the lavas of groups 3b and 4 contain phenocrysts of iron-titanium oxides. Most samples from group 3a, on the other hand, contain no oxide phenocrysts (some contain rare microphenocrysts). Furthermore, the samples from the Bia River (group 2) may be divided into two groups on the basis of the abundance of iron-titanium oxide phenocrysts. Lavas from the lower part of the section are deficient in oxide phenocrysts, in contrast to those of the upper part which contain about 1 percent oxide phenocrysts.

Amphibole (dark green to greenish brown pleochrosim) is present in one sample from Bamus (0189). It is found as anhedral grains that form, in one example, aggregates with iron-titanium oxides and some feldspar. Another aggregate contains interstitial vesicular glass, and is partly surrounded by a zone of fine-grained feldspar; this zone is surrounded by a more complete zone of fine-grained amphibole and feldspar in which the proportion of amphibole diminishes outwards.

Groundmass mineralogy. Most of the lavas examined from Bamus are fine-grained, some are glassy, and in only a few is the matrix sufficiently coarse-grained to enable all the common groundmass minerals to be identified. Plagioclase and iron-titanium oxides are ubiquitous, however, and in the more crystalline rocks augite and, less commonly, orthopyroxene have been identified.

Several rocks contain laths with low refractive indices and low birefringence which may be a silica polymorph (cristobalite or tridymite). Interstitial cristobalite is present in rocks with a coarse-grained groundmass. Several lavas from Bamus also contain tridymite which displays a characteristic "arrow-head" crystal habit. The tridymite appears to fringe amygdale-like areas, and in most cases the wedges are enclosed by isotropic glass which, in some rocks, is devitrified.

Figure 9. Poorly sorted, unstratified nuée ardente deposit in Bumba stream valley. Neg. GA/3016.

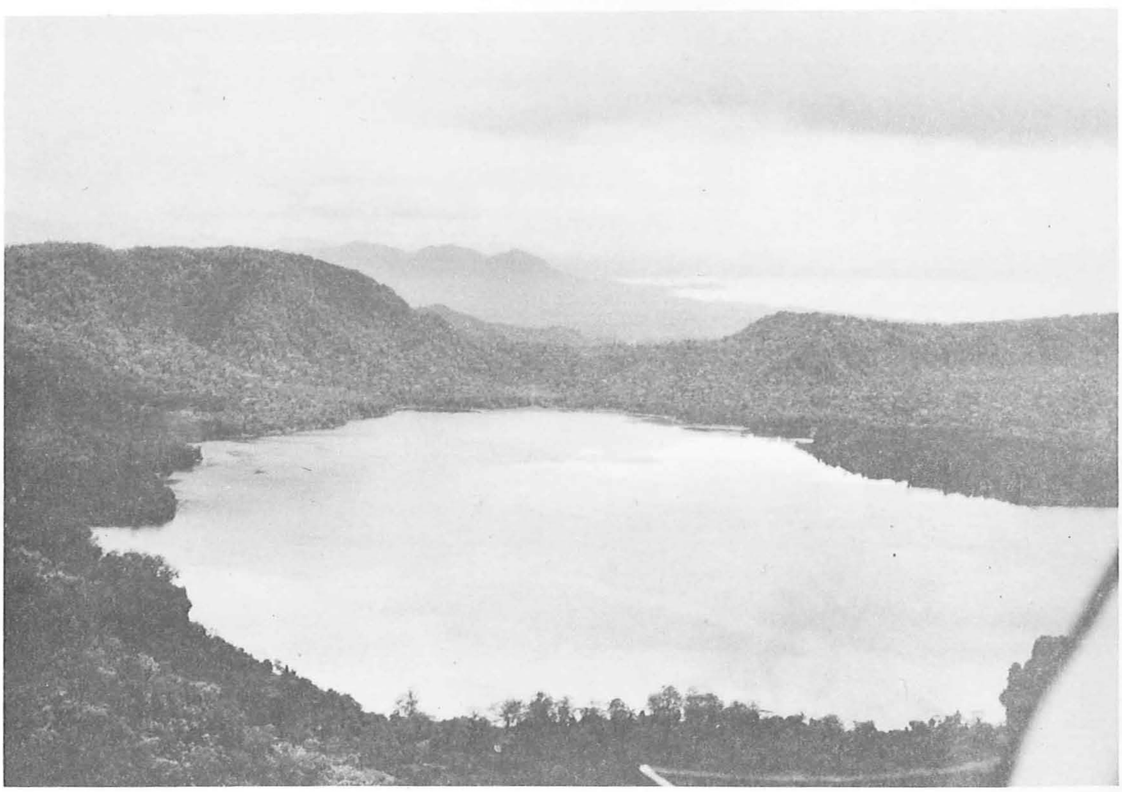

Figure 10. Lake Hargy from the northeast, showing Sulu Range through the gap in the southwestern rim of the caldera.
Neg. GA/3009.

LAKE HARGY AREA

Introduction

Lake Hargy occupies the southern part of a 13 km-wide caldera formed by collapse of a volcano, here called Hargy, whose original size was probably similar to that of Bamus and Ulawun volcanoes (figure 1). Inside Hargy caldera, a smaller volcano, Galloseulo (also called Ibi, or Eve), rises to a height of 1173 m above sea level. Galloseulo mantles part of the western rim of the caldera, and a crater is present at its summit (figure 11).

Lake Hargy is drained by the Lobu River which follows the base of a prominent west-facing escarpment from the northern shore of the lake to the northern rim of the caldera. Here, the river flows through a breach in the caldera wall, and flows northwards to become the Olimo-Tavu River which drains into the Bismarck Sea (figures 1 and 11).

Apart from villages and Bialla Plantation at the coast, the Lake Hargy area is uninhabited. It is covered mostly by rain forest and, in general, rocks are poorly exposed. Poorly drained areas and permanent swamps are present along the coast, and there are no coastal outcrops of rock. Coral reefs fringe almost the entire length of the coast shown in figure 11.

No volcanic eruptions have been reported from the Lake Hargy area. However, as there is probable thermal activity in the summit crater of Galloseulo, this volcano is considered potentially active (Fisher, 1957).

Geological Investigations

Fisher (1957) gave a short description of Galloseulo volcano, and referred to other structural and volcanic features in the vicinity of Lake Hargy. This is the only previously published account of the geology.

In recent years, several surveys have taken place in the Lake Hargy area. An investigation of timber distribution was made by the Department of Forests (Port Moresby), and a soil survey was undertaken by the Department of Agriculture, Stock, and Fisheries (Hartley, Aland, and Searle, 1967). In addition, the hydro-electric potential of Lake Hargy was investigated by the Commonwealth Department of Works, Port Moresby, for the Electricity Commission of Papua New Guinea. A scheme was proposed to take in water above the "2nd falls" of the Lobu River (figure 11), and to channel it along a raceline over 4 km long to a pondage area with 760 m of penstock. This would provide 90 m of water head leading down to a power station. Braybrooke (1969) investigated the geology of the Lobu River from Lake Hargy to the proposed site of the scheme; surface deposits were described, depths to bedrock were determined, and outcrops of lava flows were noted.

The present writer visited the Lake Hargy area on two occasions in 1969: between 7 and 12 April, and between 1 and 5 October. On the first occasion, a traverse was made from the Toiru (or Tiauru) River to the southwestern rim of the caldera (figure 11). The western side of Galloseulo was sampled, and the traverse continued eastwards to the northwestern edge of Lake Hargy, from where the upper part of the Lobu River was examined. In October, a traverse was made from Bialla Plantation to the northwestern rim of the caldera, and across the caldera floor to the Lobu River. The northern edge of Lake Hargy was sampled, and the Lobu River section was examined, from the lake northwards, to 2 km beyond the caldera rim. The traverse continued southwestwards and ended at Bialla Plantation. During a traverse in the Balima River between 20 and 25 September, 1969, R.J. Ryburn examined exposures of pyroclastic material believed to have originated from Hargy volcano.

Hargy volcano and ash-flow deposits

Cauldron subsidence has removed most of the central part of Hargy volcano, and only its peripheral slopes are preserved. The contours of these remnant slopes indicate that Hargy was elliptical in a northeast-southwest direction, ... that it grew against the edge of the Miocene limestone plateau to the east and southeast, and that it coalesced with

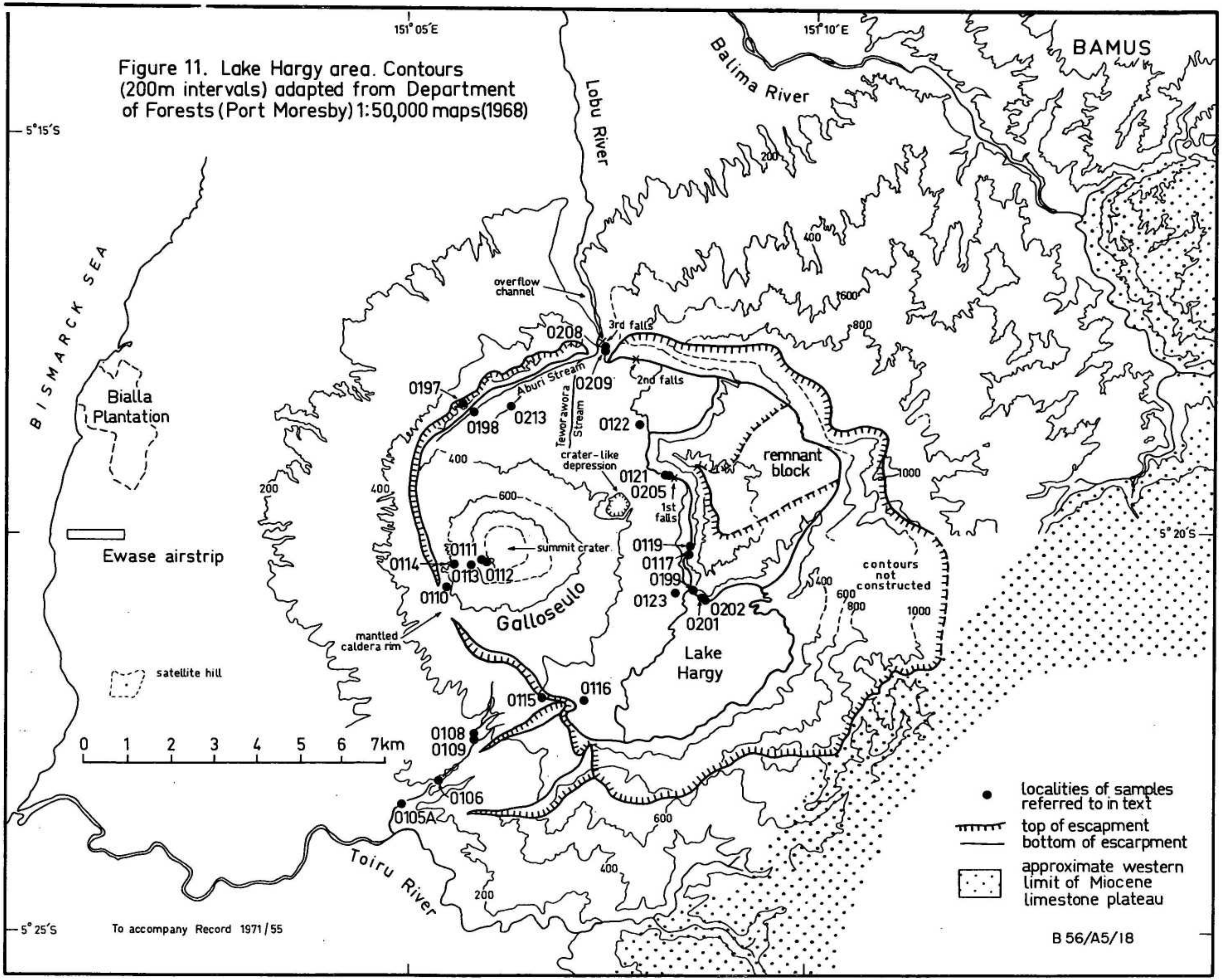

Figure 11. Lake Hargy area. Contours (200m intervals) adapted from Department of Forests (Port Moresby) 1:50,000 maps (1968)

the southern slopes of Bamus (figure 11). The Balima and Toiru (Tiauru) Rivers mark the northeastern and southern boundaries, respectively, of Hargy volcano, and the western flank levels off at sea-level.

At the 200 m contour level, the northeast-southwest diameter of Hargy volcano is about 20 km; this value compares with 16 km for Bamus, and with 18 km for Ulawun volcano. The lower flanks of Hargy volcano slope from zero at sea-level to less than 5^{o} immediately outside the caldera rim. Assuming these slopes increase continuously upwards at the same rate as those on Bamus and Ulawun, the original height of Hargy volcano must have been at least equal to the present-day heights of Ulawun and Bamus (about 2300 m above sea-level).

Exposures of Hargy volcano are limited. The best outcrops are those in the Lobu River, and in the northern tributaries of the Toiru River on the southwestern flank of the volcano. Exposures of Hargy volcano are probably present on parts of the steep, vegetation-covered, caldera escarpment, but most of these are not easily accessible. Lava flows, with scoriaceous upper and lower surfaces, and interbedded scoria layers, appear to be the dominant constituent of Hargy volcano, indicating that, like Bamus and Ulawun, it is a stratovolcano. Four dykes, less than 2.5 m wide, were observed in a northern tributary of the Toiru River; three of these trend roughly east-west.

A pyramidal hill on the western outer flanks of Hargy volcano, close to the coast, is probably a satellite eruptive centre (figure 11). The hill is over 200 m high. It has no summit crater, is covered entirely by rainforest, and could have been formed either before or after formation of Hargy caldera.

The southwestern and western slopes of Hargy are planar, and are cut only by a few stream gorges. This uniform topography is due to a thick deposit of pumiceous fragmental material which mantles this part of Hargy volcano. Most of the material appears to have been deposited by ash-flows which were probably erupted when the caldera of Hargy volcano was formed. The deposits are porous, and rain-water easily percolates through them. No erosion of the deposits has taken place, except at the edges of a few stream gorges, which in places are more than 100 m deep, and at the bottom expose lava flows of Hargy volcano.

The best observed exposures of the ash-flow deposits are in the Toiru River and its tributaries (figure 11). Here, many outcrops show up to 10 m of massive, unsorted, unbedded fragmental material, much of which consists of pumiceous clasts ranging between ash and lapillus sizes. Some deposits also contain dark rounded boulders of lava up to 2.5 m in diameter. A few exposures show more than one layer of fragmental material. For example, in one outcrop close to the caldera rim, a layer about 8 cm thick consisting of dark highly vesicular cinders separates an underlying crudely-bedded deposit from a 1 m-thick layer of unbedded pumiceous material; this is overlain by a layer, at least 1 m thick, of unsorted pumiceous debris rich in lava clasts. One outcrop of unbedded fragmental material preserves a mould shaped like an upright log.

In the Toiru River, the pumiceous fragmental material has the crude columnar structure typical of non-welded or poorly-welded ash-flow deposits from other volcanic areas (cf. Smith, 1960). In some layers close to the southwestern rim of the caldera there is also clear evidence of flattening of pumice fragments. Some boulders in the Toiru River contain obsidian lenses, and in thin section they show highly deformed glass shards, indicating more intense degrees of welding (figure 12). These rocks have not been found in situ.

Pumiceous pyroclastic deposits are also present in the Balima River valley (figures 3 and 11). At one outcrop, about 7.5 km upstream from Gigipuna village, a massive deposit consists of unsorted angular fragments of pumice up to 2.5 cm in diameter, and smaller clasts of dark scoriaceous lavas, in a matrix of fine ash. The deposit contains sub-horizontal holes where tree branches have weathered out. Hartley, Aland, and Searle (1967) also observed similar deposits in the Balima River. They commented on the different compositions of the clasts ("more basic gravel dispersed through the pumice ash which is probably more acidic ... "), and explained the phenomenon as due to concurrent deposition of air-fall ashes of different compositions from Bamus (or Ulawun) and Galloseulo volcanoes. However, the absence of sorting, the mixture of pumiceous and lava clasts, and the preservation of log and tree moulds, are all features of materials deposited by nuées ardentes. Furthermore, it seems likely that the pumice deposits in the Balima River were laid down by nuées which were erupted at the time of cauldron subsidence, and are probably the same age as the welded pumiceous deposits on the south-western flank of Hargy volcano. Other bedded pumice deposits, some of which show mantle bedding, are also present in the Balima River. These were probably deposited by air-fall from ash-clouds possibly associated with the formation of the nuées ardentes, or else they are the reworked products of nuée or air-fall materials.

Explosive eruptions of ash-flow and air-fall pyroclastic material have accompanied cauldron subsidence on many volcanoes throughout the world (see, for example, Williams, 1941; Smith, 1960), and it is assumed that the ash-flow deposits on the outer flanks of Hargy volcano were also erupted at the time of cauldron subsidence. As in the case of most calderas, the source of the Hargy ash-flow deposits is speculative. Although it is commonly assumed that pyroclastic eruptions take place at the central vents of a volcano, producing a void in the underlying magma chamber, thereby causing cauldron collapse (the so-called "Krakataun" calderas of Williams, 1941), it is also possible that the explosive eruptions take place at ring fractures formed as a result of cauldron subsidence (for a more detailed discussion of this problem, see Johnson, 1969).

Before cauldron subsidence, the eastern flanks of Hargy volcano may have been built up to the level of the Miocene limestone plateau to the east, and if so, lavas and ash-flows from the volcano would have poured onto it (figure 11). Air-fall pyroclastic material from Hargy - and probably from other volcanoes in the vicinity (figure 1) - would also have been deposited on the limestone during the growth of Hargy volcano. Hence, the western limit of the plateau limestone is difficult to delineate on the air-photographs, and the limit shown in figure 11 is approximate.

Hargy caldera

The collapse which engulfed most of the central part of Hargy volcano produced a caldera 13 km wide from eastsoutheast to westnorthwest and 9.5 km wide from northeast to southwest. The caldera covers about 95 sq. km, and is similar in size to the Rabaul caldera (Fisher, 1939a; Heming, in preparation) and to Dakataua caldera on the northern end of Willaumez Peninsula (Branch, 1967; Lowder and Carmichael, 1969; figure 1).

The lowest part of the caldera floor, in the south, is occupied by Lake Hargy (figures 10 and 11). The lake is about 4.75 km long from southwest to northeast, and about 2.75 km wide at its widest point from northwest to southeast; its area is about 9 sq. km. The water-level in the lake is about 340 m above sea-level. The maximum depth of the lake is unknown.

Figure 11 shows that the northwestern, southwestern, and southeastern sides of the caldera are more or less straight, and that the northeastern side is arcuate. The slopes of the southeastern part of the caldera wall are mostly less than 35°. This contrasts with the remainder of the caldera wall which is precipitous, and slopes into the caldera at more than 60°. In figure 11, the southeastern rim of the caldera is shown intersecting the Miocene limestone plateau, and it is presumed that some limestone is preserved in this part of the caldera escarpment.

The top of the escarpment bounding the western part of the caldera is mostly about 480 m above sea-level, and is lower than the remainder of the caldera rim, which ranges from about 600 m to over 1000 m above sea-level. Between each of these sections of the caldera rim there are two low parts. The lowest part is a steep-sided notch at about 250 m above sea-level in the north, through which the Lobu River drains from Lake Hargy to the sea (figure 11). This low-point possibly represents a truncated major valley which originally drained the northern slopes of Hargy volcano, and has since been deepened by overflow from Lake Hargy; it is possibly analagous to the major valley draining the northwestern flank of Ulawun volcano at the present day (Johnson, 1970a).

The other low part of the caldera escarpment is a 1000 m-long section in the southwest, which is a little over 400 m above sea-level (figures 10 and 11). This low section appears to have been produced at the intersection of a linear graben on the southwestern flank of Hargy volcano with the caldera rim. The graben is bounded by two parallel escarpments, about 1 km apart, trending southwest from the caldera rim (figure 11). The northern escarpment is about 2 km long; the southern one is about 3 km long, and at its highest point is over 200 m higher than the northern escarpment. Between the two escarpments, the uniform slopes of the volcano are relatively undissected.

It is believed that the linear graben formed before cauldron subsidence. Originally, the graben probably extended farther to the northeast, straddling Hargy volcano in the same way as a possible linear graben straddles Ulawun volcano (Johnson, 1970a). During cauldron subsidence, the northeastern end of the graben was engulfed, but the southwestern end was preserved. Stream gorges within the graben were probably filled by ash-flows erupted concomitantly with cauldron subsidence.

The most striking structural anomaly of the Hargy caldera is the preservation of a "remnant block" against the northeastern wall of the caldera (figure 11). This block is bounded on three sides by steep escarpments which are between about 280 and 420 m above the level of the caldera floor. The escarpments on the northwestern and western sides are cuspate, and the upper surface of the block dips a few degrees to the northeast.

The most likely interpretation for the origin of this block is that it is a remnant of the central part of Hargy volcano which did not collapse as far as the remainder of the caldera area. During cauldron collapse, the subsiding block is envisaged as having broken into at least two pieces, one of which, the "remnant block" became jammed between the caldera wall and the rest of the sinking cauldron block. Alternatively, the remnant block could be interpreted as a portion of the caldera floor which was raised after the caldera had formed. In this case, the top of the block could be covered with post-caldera lava flows.

The southeastern escarpment of the remnant block is in almost direct line with the northern escarpment of the linear graben (figure 11). Although this alignment may be fortuitous, it is possible that both escarpments are parts of a continuous fracture. If this is so, then it is also possible that the fault bounding the southeastern margin of the remnant block may have been part of the northern escarpment of the linear graben. Thus, the structural features of the Lake Hargy area may be considered as having resulted from the interaction of two major events - formation of the southwest-northeast graben, and cauldron subsidence.

Galloseulo volcano and thermal activity

Galloseulo is a symmetrical volcano, with a summit crater, which has grown in the western part of Hargy caldera to about 830 m above the level of Lake Hargy. According to the U.S. Army 4" to 1 mile map of Central New Britain (1943), the height of Galloseulo above sea-level is 3848' (1173 m).

Galloseulo rises above the western rim of the caldera, and lavas from the volcano have spilled over the caldera escarpment onto the western flank of Hargy volcano. The slope of the flanks of Galloseulo decreases from a maximum of about 17° near the summit, to zero on the lowest parts of the caldera floor.

Galloseulo is cut by closely-spaced radial streams, and the absence of deep gullies testifies to the youthfulness of the volcano. Exposures on the outer flanks of Galloseulo are limited, and most samples collected from the volcano are from loose blocks of lava in stream beds. These samples are dark, fine-grained, and sparsely porphyritic: the five samples in group 4 of Table 3 show only 3-7 percent total phenocrysts. Chemical analyses of these samples show they are dacites, and are more silica-rich than the other analysed samples from the Lake Hargy area (see page 27).

Outcrops of fresh lava and agglomerate are found in the Aburi and Teworawora Streams at the northwestern edge of the caldera floor (figure 11). These rocks are believed to be post-caldera, and to have been produced at an early stage in the development of Galloseulo. No other exposures of the lower part of Galloseulo have been found.

A crater-like depression, about 700 m across, is present about 2.5 km eastnortheast of the summit of Galloseulo (figure 11). The floor of the caldera rises slightly to the rim of this depression, suggesting the presence of remnant constructional slopes of a satellite cone; no rocks are exposed, either inside or outside the depression.

A crater is present at the summit of Galloseulo, but because of cloud cover, it is not shown on the available aerial photographs of the area. However, according to Fisher (1957), "The original crater has a total diameter of approximately 700 m., but later activity has resulted in the formation of a double crater, possibly 60 m or more deep, in the S.S.E. half of the original crater. The summit has not been visited (to the writer's knowledge), but close examination from an aircraft shows that steam is being given off in small quantity at several places around the crater". Owing to poor visibility, caused by rain and low cloud, the state of this crater could not be observed by the writer when the southwestern side of Galloseulo was climbed on 9 April, 1969. A brief glimpse through a gap in the clouds showed the vegetation-covered opposite side of the crater, but no thermal activity was observed. Thermal activity was seen by Mr D. Lloyd on a visit to the crater during the period 22 August to 2 September, 1967. According to Brother F. Kleinelanghorst of Ulamona Mission, Mr Lloyd "noticed that there is stream emitting from 5 vents on the inside of the crater. The crater is about 100 feet deep and heavily vegetated. The vents are about 70 feet from the top of the mountain ... there was nothing that looked or smelled like sulphur". (letter dated 7 September, 1967, on file VF/9A, Central Volcanological Observatory, Rabaul)

Apart from the summit crater of Galloseulo, there is only one known occurrence of thermal activity in the Lake Hargy area. Braybrooke (1969) reported a "number of warm springs (warmer than 90°F)" which flowed into the lower reaches of a stream draining the northern part of the caldera (figure 11). Small quantities of a fine-grained white deposit (possibly silica) were being deposited on stream boulders when the locality was visited by the writer in April, 1969, but no other sublimates were present. The springs were discharging small amounts of water which were noticeably warmer than the waters of the adjacent stream.

Post-caldera sediments

On parts of the caldera floor there are outcrops of well-bedded volcanic sediments which overlie the youngest lava flows of the caldera. These sediments are exposed in the banks of the Lobu River, and in Teworawora stream (figure 11). Most of the sediments range between volcanic silty-clays and medium sands, but rudaceous sediments are preserved locally. The beds mostly range in thickness from one to fifty centimetres, and they show a wide colour range (brown, grey orange, and buff are common). Load cast and "flame" structures are preserved in some exposures, and in one exposure well-formed accretionary lapilli are found. In any one outcrop, thicknesses of sediment up to 6 or 7 m are exposed. Sediment thicknesses in the Lobu River section are probably greater, as parts of the river bank, which probably consist entirely of sediments, are up to 16 or 17 m above the present day river level. More detailed descriptions of these sediments are given by Hartley, Aland, and Searle (1967) and by Braybrooke (1969).

The sediments are considered to be lacustrine deposits, and they indicate that Lake Hargy once extended between the eastern slopes of Galloseulo and the western side of the remnant block, and spread out in the northern part of the caldera. The lake presumably overflowed at the notch in the northern wall of the caldera, and as downcutting proceeded, so the lake level fell, and the northern margin of the lake retreated southwards until it reached its present-day position. Most of the sediments deposited in the lake were presumably derived from rocks exposed inside the caldera. Some material, however, such as the accretionary lapilli, was probably deposited by ash clouds originating from Galloseulo, Bamus, and Ulawun volcanoes.

Petrology

In contrast to the uniform composition of the lavas from Bamus volcano, those from the Lake Hargy area show a range of compositions between olivine-bearing types and dacites.

Fifty-three rocks have been examined in thin section. Modal analyses of twenty-one of these are given in Table 3, and their localities are listed and divided into four groups in Table 4. Samples of group 1 were collected from the pre-caldera Hargy volcano. Those of group 4 are from Galloseulo, the post-caldera volcano, and those of group 3 are from the flat caldera floor and possibly represent older flows of Galloseulo. Samples from the Lobu River section and northern margin of Lake Hargy are listed in group 2.

In common with most Quaternary volcanoes along the north coast of New Britain, the lavas of the Lake Hargy area are porphyritic (cf. Johnson, 1970a,b). In common with lavas from Lolobau Island the least porphyritic lavas are those which are more silica-rich (cf. Johnson, 1970b; dacitic rocks of group 4, Table 3). The phenocrysts are plagioclase, pleochroic orthopyroxene, clinopyroxene (dominantly augite), iron-titanium oxide, and rare olivine.

Plagioclase is the most abundant phenocryst. In the samples of Table 3, it ranges between 3 and 41 percent, and is at least twice as abundant as any other phenocryst phase present. Sample 0115 is unusual in containing phenocrysts of plagioclase only.

The plagioclase phenocrysts of the Lake Hargy lavas are similar to most others in Quaternary lavas along the north coast of New Britain: they are zoned (oscillatory and normal zoning are common), many of them contain numerous groundmass inclusions, and some form aggregates with, or without, ferromagnesian phenocrysts. The compositions of plagioclase phenocrysts from six rocks in Table 3, determined by the combined Carlsbad-Albite twin method, range between An_{68} and An_{81} (labradorite-bytownite).

Clinopyroxene. Phenocrysts of augite are present in many lavas from the Lake Hargy area, but in the majority of samples in Table 3 the amount is 1 percent or less. Some augite phenocrysts are optically zoned. Two rocks (0111 and 0122) contain rare microphenocrysts of a clinopyroxene with a small 2V (less than 20°); this pyroxene may be either pigeonite or sub-calcic augite.

Pleochroic <u>orthopyroxene</u> phenocrysts are present in many samples but, as in the case of augite phenocrysts, they constitute only 1 percent or less of most rocks. Many orthopyroxene phenocrysts are rimmed by fine-grained narrow zones of a clinopyroxene that appears to be augite. In some rocks, orthopyroxene grains form distinctive monomineralic aggregates.

<u>Magnesian olivine</u> phenocrysts are present in only a few rocks. They are most conspicuous in dykes (0105A, B) and lavas (0108) of group 1, but they are also present in some lavas from other parts of the area (for example, samples from the 1st falls of the Lobu River; 0205 and 0121).

In most olivine-bearing lavas, the olivine phenocrysts are surrounded by zones of coarse-grained orthopyroxene*, indicating that the rocks are silica-saturated (tholeiitic). In two samples (0121 and 0205) a zone of clinopyroxene (probably augite, but possibly a Ca-poor pyroxene) is present on the outer edge of hypersthene grains that mantle olivine phenocrysts.

Olivine phenocrysts in the dyke rocks are completely or partly pseudomorphed by "iddingsite". As these phenocrysts have no rims of Ca-poor pyroxene, they indicate that olivine was pseudomorphed before it had opportunity to react with liquid and form pyroxene. The same conclusion was reached for other olivine-bearing rocks from Bamus volcano (page 12), Lolobau Island, and Likuruanga volcano (Johnson, 1970b).

Iron-titanium oxide phenocrysts are commonly present, but in all the samples listed in Table 3 the amount is less than 1 percent. They are most abundant in lavas of group 4. The phenocrysts are present as individual grains, and in aggregates with, and as inclusions in, silicate phenocrysts.

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* An unidentified pyroxene forms narrow, fine-grained rims around the olivine phenocrysts in sample 0108; this pyroxene could be a monoclinic variety, either pigeonite or sub-calcic augite.

Groundmass mineralogy. The groundmass of most lavas ranges from glass with microlites to finely crystalline material in which the most readily identified phases are plagioclase, clinopyroxene, orthopyroxene, and iron-titanium oxide. In some rocks, clinopyroxene forms zones on the prism faces of groundmass orthopyroxene laths. Pigeonite or sub-calcic augite (that is, clinopyroxene with a 2V between 0 and 30^{o}) is thought to be present in some rocks (in particular, those containing olivine phenocrysts), but in most cases clear interference figures cannot be obtained because of small grain size. In several rocks, fine-grained interstitial material with low refractive indices and low birefringence indicates the presence of silica minerals and alkali feldspar. Interstitial cristobalite can be identified in some rocks.

In a few samples, clearly defined pale patches of salic minerals - plagioclase, probable silica phases, and possibly alkali feldspar - are enclosed by darker material made up of pyroxene, iron-titanium oxide, and plagioclase. In some of these rocks, the light-coloured patches are surrounded by a narrow dark zone enriched in iron-titanium oxides. A similar texture is present in lavas from Lolobau Island (Johnson, 1970b; see, for example, sample 53NG1049). In sample 0111, from Galloseulo volcano, groundmass pyroxene and plagioclase laths are enclosed by irregular areas with low refractive indices and low birefringence; these areas show no twinning, and they are probably alkali feldspar.

More extensive coarser-grained salic areas are present in samples 0197 (fissile talus block on the northwestern caldera wall) and 0119 (talus block probably derived from the "remnant block"). In 0197, the light-coloured areas are present as patches, irregular layers, and vein-like stringers which cut across the remainder of a groundmass containing pyroxenes, iron-titanium oxide, and plagioclase. The minerals in the salic areas are quartz, high temperature polymorphs of silica, and possibly alkali feldspar. Quartz is also present as a groundmass phase with possible alkali feldspar in sample 0119. The salic minerals in these rocks appear to be primary, and the layers and stringers may represent local concentrations of late-stage residual liquids. Quartzo-feldspathic material has a granophyric texture in one plutonic clast (0109) collected as a loose pebble in the northern tributary of the Toiru River; this clast is probably an accidental inclusion derived from the ash-flow deposits.

Samples 0198 and 0213, which are probably from the same flow (Table 3), also show unusual groundmass textures. In both rocks, dense patches enriched in iron-titanium oxides are enclosed in light brown glass, which is free of oxide minerals but contains plagioclase and pyroxene.

Finally, distinctive groundmass textures are associated with vesicles in samples 0105A, a dyke rock, and 0110 and 0114, lavas from Galloseulo volcano. In each rock, vesicles are rimmed by material which is more glassy than the crystalline groundmass. In 0110 and 0114, opaque laths, which are possibly ilmenite, are concentrated in the vicinity of vesicles, but are absent throughout the remainder of the groundmass. These features are probably the result of distinctive chilling and oxidation conditions which prevailed adjacent to the vesicles at the time of their formation. Alternatively, they may be examples of "segregation vesicles", that is, late-stage material which has migrated to, and crystallized at, the margins of cavities (Smith, 1967).

Chemical analyses of rocks from the Lake Hargy area will be presented and discussed in a separate report dealing with the petrochemistry of all the Quaternary volcanoes of the north coast of New Britain. In this Record, however, it is noted that analyses of three rocks from Galloseulo volcano (group 4 in Table 3) show silica values in the range 64.8 to 65.52, indicating dacitic compositions, and that analyses of six rocks from elsewhere in the Lake Hargy area show less than 63 wt. percent silica, indicating andesitic compositions.

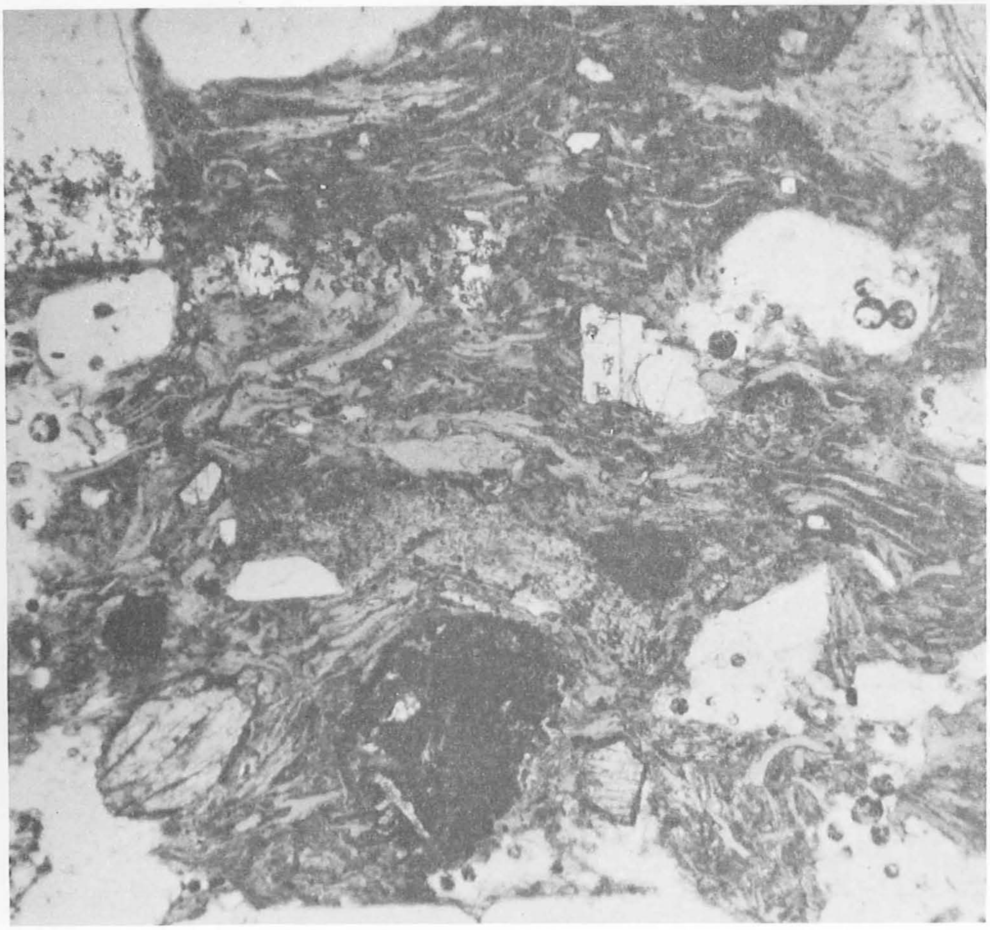

Figure 12. Deformed shards in boulder from a welded ash-flow deposit, southwestern flank of Hargy volcano; magnification about 36X Neg. M/993

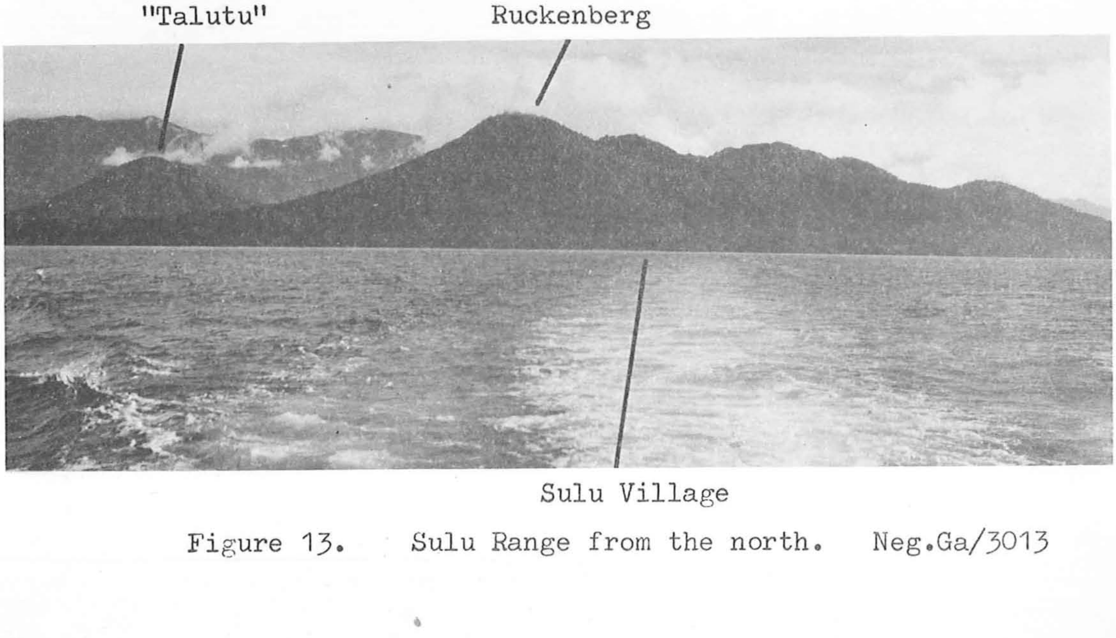

Figure 13. Sulu Range from the north. Neg.Ga/3013

SULU RANGE

Topography and Geology

Sulu Range is a low-lying cluster of volcanic cones about 25 km southwest of Lake Hargy (figures 1, 10 and 13). The cones cover about 42 sq. km, and none of them rises more than about 550 m above sea-level. The volcanic nature of Sulu Range was recognized by Stanley (1922) who stated that the hills appeared to be "in part, active". Apart from this brief reference, no geological account of Sulu Range has been given.

R.P. Macnab, R.J. Ryburn, and the writer examined the Sulu Range between 4 and 6 October, 1969. Most samples collected during this period were from boulders in streams and on beaches. Outcrops were observed mainly at the coast.

Sulu Range consists of a group of coalescent volcanic cones, forming the main ridge of the Range, and two separate cones - Ruckenberg in the north, and "Talutu" (local name) in the east (figures 13 and 14). The volcanoes of the main ridge are simple cones which form an arcuate ridge extending from "Malobu" (local name), the highest point, in the south (about 520 m above sea-level) to the northwest. No summit craters are preserved. The cones are not deeply dissected, and rocks are poorly exposed.

The extension of the main ridge of Sulu Range coincides with a low-lying promontory, Lara Point, which contains a small lake (figure 14). Fine-bedded volcanic sediments and pumice layers are exposed on the beaches of the promontory, and lava crops out at two points. The promontory appears to have been formed by lavas that flowed from the northwestern end of the main ridge of Sulu Range, and which have been covered by volcaniclastic material. The lake occupies a shallow depression on the promontory.

Ruckenberg is the largest volcanic cone in Sulu Range (figures 13 and 14). According to the U.S. Army 1 inch to 1 mile maps (1943), it is over 550 m above sea-level, and is about 3.5 km wide at its base.

Ruckenberg is separated from the main ridge of Sulu Range to the south by a saddle which is about 230 m above sea-level at its highest point. A shallow crater, 250-300 m in diameter, occupies the summit of Ruckenberg, and to the west remnants of an older crater wall are preserved. Like the main ridge of the Range, Ruckenberg is not deeply dissected, and rock exposures are rare. However, lava flows from Ruckenberg are exposed at the coast, where they are associated with beds of accretionary lapilli.

Talutu is a volcanic cone separated from the main ridge of Sulu Range to the west (figure 14). It is over 300 m high, and has no summit crater.

Petrology

The rocks of the Sulu Range show a wide range of compositions - from basic lavas, with up to 7 percent olivine phenocrysts, to lavas of intermediate composition, to rhyolitic glasses containing abundant phenocrysts of quartz and, in some samples, amphibole.

Forty-nine rocks from Sulu Range have been examined in thin section. Table 5 represents modal analyses for twenty-one samples which are divided into five groups; the localities of these samples are described in Table 6. Chemical analyses of four rocks are available, but these will be presented and discussed in greater detail elsewhere.

All the rocks examined are highly porphyritic. All but four of the twenty-one samples listed in Table 5 contain between 20 and 38 percent phenocrysts. In order of decreasing abundance, these phenocrysts are plagioclase, clinopyroxene (augite), pleochroic orthopyroxene, olivine, quartz, amphibole, and iron-titanium oxides.

Plagioclase. In common with most Quaternary lavas in New Britain, plagioclase is the most abundant type of phenocryst in the rocks of Sulu Range: fourteen of the twenty-one samples in Table 5 contain 10 percent or more plagioclase phenocrysts (cf. Johnson, 1970a,b; Johnson, Davies, and Palfreyman, 1971; see also Tables 1 and 3). In some lavas,

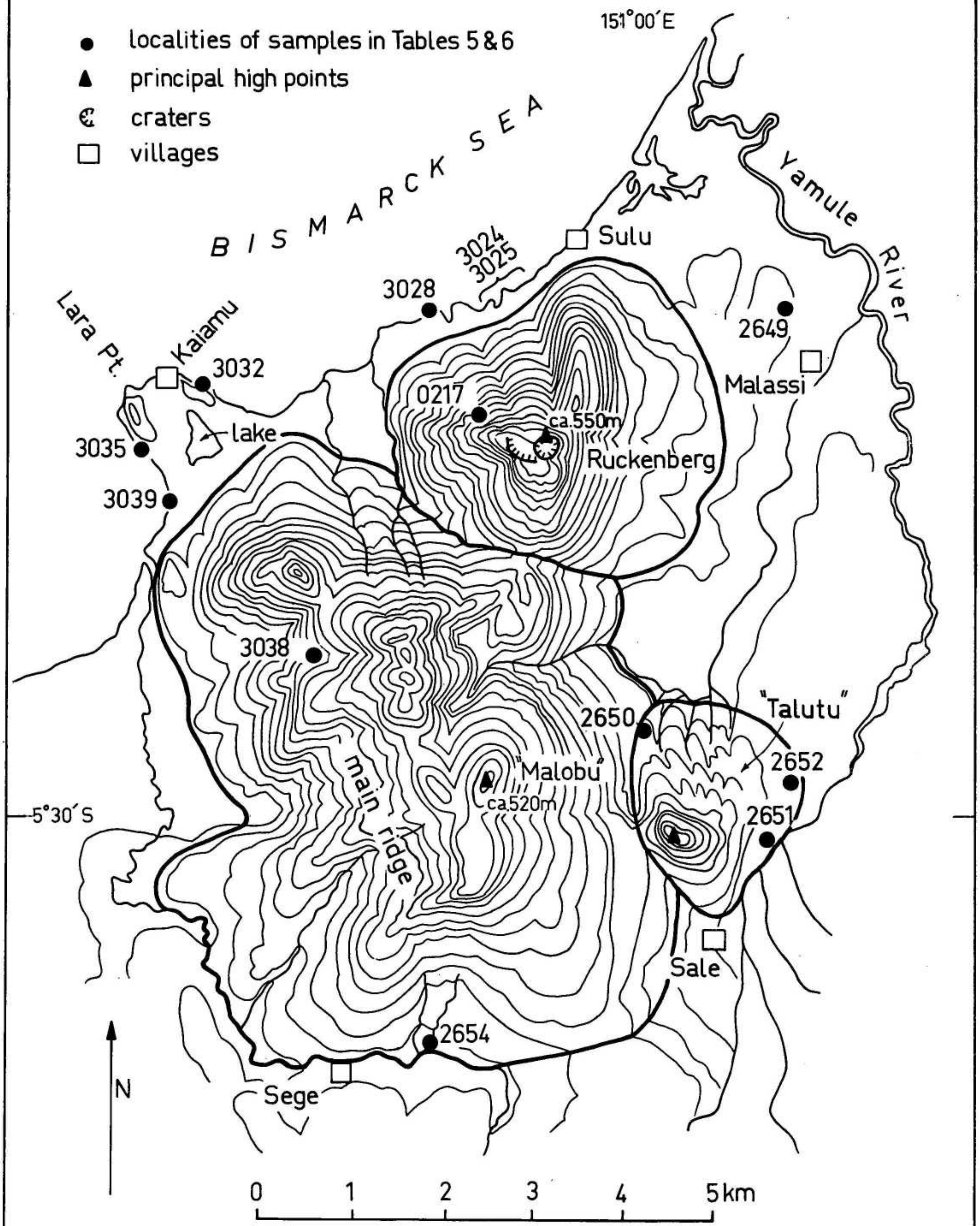

Figure 14. Sulu Range. Form lines (intervals about 100') adapted from U.S. Army 1" to 1 mile maps (1943)

To accompany Record 1971/55

B56/A5/15

there is a marked deficiency of ferromagnesian minerals, and plagioclase is by far the most dominant type of phenocryst (see, for example, samples 2649 and 3025B in Table 5). However, in other rocks - in particular those from Ruckenberg and Talutu cones (groups 1 and 2 in Table 5) - olivine or pyroxene phenocrysts, or both, are more abundant than plagioclase phenocrysts.*

The plagioclase phenocrysts of Sulu Range are strongly zoned, and many of them show oscillatory zoning. They form aggregates, in many cases with other phenocryst minerals, and commonly contain inclusions of groundmass material and phenocryst minerals. Determinations of composition by the combined Carlsbad-Albite twin method for plagioclase phenocrysts in three rocks (2649, 2654A, 3024) gave anorthite percentages in the range An_{68-80} (mainly bytownite). Plagioclase phenocrysts with combined Carlsbad-Albite twinning are rare in the quartz-bearing lavas, but three determinations gave anorthite percentages of 48, 55, and 65 (andesine-labradorite).

Clinopyroxene. Augite is the most common type of ferromagnesian phenocryst in the lavas of Sulu Range. It is present in all but one of the twenty-one samples in Table 5, but in eight of these the amount is 1 percent, or less. Augite is most common in the olivine-bearing lavas, and least common in the quartz-bearing ones. Some augite phenocrysts show slight zoning, and a few have cores of pleochroic orthopyroxene.

Orthopyroxene. Pleochroic orthopyroxene (hypersthene or bronzite, with pale green to pale reddish-brown pleochroism) is present as phenocrysts in many lavas, but in only six of the samples in Table 5 is the amount more than 1 percent. Orthopyroxene is absent from, or deficient in, lavas containing olivine phenocrysts. Most orthopyroxene phenocrysts have rims of clinopyroxene which, where well-developed, have been identified as augite.

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* Other samples described in this Record in which ferromagnesian phenocrysts dominate over plagioclase phenocrysts are 3006 (Table 1) and 0205 (Table 3).

Olivine phenocrysts are most common in lavas from Ruckenberg and Talutu (groups 1 and 2 in Table 5); in six of the seven samples listed in Table 5, olivine makes up between 2 and 7 percent. In some rocks, olivine phenocrysts are euhedral, but in others they are rounded as though some resorption has taken place.

In some olivine-bearing rocks, narrow zones of pyroxene, in some cases identified as orthopyroxene, surround the olivine phenocrysts. These zones show that the olivine phenocrysts bear a reaction relationship with silica-saturated liquid, and that the lavas are tholeiitic. Iron-titanium oxides form peripheral zones on some olivine phenocrysts, and in a few places the olivine is completely pseudomorphed by them; these phenocrysts do not have well-developed coronas of pyroxene.

In a few rocks, the olivine phenocrysts are replaced by "iddingsite". In sample 2654A, the iddingsitized olivine is surrounded by prominent grains of orthopyroxene, indicating that olivine had reacted to form calcium-poor pyroxene before it was replaced by iddingsite. In other samples, however, no coronas of pyroxene are present, suggesting the olivine phenocrysts may have been iddingsitized before they had opportunity to react with liquid and form pyroxene.

Iron-titanium oxide phenocrysts are present in about half of the rocks listed in Table 5, and in all these the amount is about 1 percent, or less. They are most abundant in lavas containing quartz phenocrysts, but they are also present in some olivine-bearing lavas. Iron-titanium oxides are present as separate phenocrysts, and as inclusions in silicate phenocrysts.

Quartz phenocrysts are present in samples collected from loose blocks on Lara Point (group 5), and in a gully on the western flank of the Sulu Range (group 4). In most hand specimens, the quartz is seen as distinctive, colourless, equant grains with a glassy lustre. In thin section, the larger quartz phenocrysts (up to about 7 mm in diameter) are seen to be anhedral, and smaller grains are spherical. Some rare quartz grains are rimmed by laths of augite (for example, 2654A and 3031).

Whole-rock chemical analyses of quartz-bearing samples 3032A and 3032C show silica percentages of 72.4 and 71.2 respectively, corresponding to rhyolite compositions.

Amphibole phenocrysts are present in some of the quartz-bearing rocks. The amphibole forms elongate crystals up to about 4 mm long. In samples 3038B and 3043, the pleochroic scheme of the amphibole is: X = light brown, Y = greenish-brown, Z = brownish-green, indicating common hornblende compositions (Deer, Howie, and Zussman, 1963).

Polymineralic grains. Euhedral grains consisting of more than one mineral phase are found in some quartz-bearing lavas from Sulu Range. The grains are variable in composition and texture, but in several examples they consist of a pyroxene host (augite or orthopyroxene) that contains aligned laths of another pyroxene, or plagioclase, or both, and grains of iron-titanium oxides (for example, 3043, 3038F, 3032A). In other grains, for example in 3032B, there is a crude alignment of numerous pyroxene laths of one compositions, some of which are in optical continuity.

Groundmass mineralogy. The groundmass of lavas from Sulu Range range between a fine-grained crystalline material in the basic (with olivine phenocrysts) and intermediate rocks to clear glass in the acid ones (with quartz phenocrysts).

The most easily recognized minerals in the basic and intermediate rocks are plagioclase, clinopyroxene, orthopyroxene, iron-titanium oxide, and glass. The principal clinopyroxene is augite, but in some samples a calcium-poor variety (pigeonite or sub-calcic augite, with a 2V of 0-30°) is present (for example, sample 2650A). The presence of a calcium-poor pyroxene is suspected in several other rocks, particularly those containing olivine phenocrysts, but in many of these, owing to fine grainsize, it is difficult to obtain suitable interference figures.

In a few basic and intermediate rocks, groundmass orthopyroxene laths are rimmed by clinopyroxene, and in an oxidized sample, 3038E, groundmass pyroxene grains are pseudomorphed by iron-titanium oxides. In a few samples, colourless interstitial material of low birefringence and low refractive indices is probably silica (cristobalite or tridymite). Cristobalite has been identified in the groundmass of samples 3032C, and arrowhead crystals of tridymite are present in vesicles in sample 3038G.

The groundmass of rocks containing abundant quartz phenocrysts ranges from glass - in some cases obsidian (for example, samples 3038B and 3043) - to extremely fine-grained material in which the most common mineral phases are plagioclase, iron-titanium oxide, orthopyroxene, and clinopyroxene (probably augite). In two fine-grained acid rocks, 3031 and 3038E, opaque laths in the groundmass are possibly ilmenite. The groundmass of sample 3038H was probably largely glass, but devitrification has produced distinctive axiolitic and sheaf-like aggregates of microlites. Other parts of the groundmass of this sample consist of more coarsely crystalline areas, enriched in salic minerals, and depleted in iron-titanium oxides.

The groundmass of samples 3032A and 3032C (loose blocks from Lara Point) is dominantly glass. In hand specimen the colour of these rocks if off-white, and in thin section, the glass is seen to be pumiceous with drawn-out microvesicles that "flow" around phenocrysts. The texture resembles eutaxitic structures in ash-flow deposits. However, no shards are present, and the blocks are interpreted as frothed rhyditic lava.

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TABLE 1 MODAL ANALYSES OF 25 ROCKS FROM BAMUS VOLCANO

Group	Sample number (prefix 51NG)	volume % phenocrysts					
		Plagio-clase	Olivine	Ortho-pyroxene	Clino-pyroxene	Fe/Ti oxide	Total % phenocrysts
1.	2604	25	-	1	<1	<1	26
	2607	35	17	-	6	2	60
	2614	28	<1	1	<1	<1	29
2.	3006	1	2	12	6	(a)	21
	3008	19	-	<1	<1	-	19
	3009	27	-	1	<1	<1	28
	3016	33	<1	2	<1	<1	35
	3020	21	<1	8	2	<1	31
	3021	27	-	7	1	<1	35
3.(a)	0185	18	-	<1	<1	-	18
	0187	14	-	1	<1	-	14
	0193	27	-	4	1	<1	32
	0195D	29	-	1	1	-	31
	0195G	33	-	1	<1	(a)	34
	0195M	14	-	1	<1	-	15
	0195T	16	-	1	<1	-	17
3.(b)	0175	37	-	2	3	1	43
	0191A	36	-	3	<1	1	40
	0195U	36	<1	1	<1	<1	37
	0195X	33	-	5	1	1	40
4.	0166	29	-	7	2	1	39
	0170	28	-	5	1	1	35
	0171	28	-	<1	<1	<1	28
	0174A	29	<1	8	2	1	40
	0174D	34	1	8	2	1	46

(a) rare microphenocrysts

TABLE 2 LOCALITY INDEX FOR SAMPLES OF TABLE 1

Group	Sample	Locality description
1. Balima River section	2604	*in situ* columnar-jointed lava flow.
	2607	*in situ* lava flow.
	2614	talus, beneath *in situ* lava flow.
2. Bia River section	3006, 3008, 3009, 3016, 3020, 3021	*in situ* lava flows, arranged in stratigraphic order from oldest (3006) to youngest (3021)
3. (a) Deep gorge on western flank; most of these samples are older than northsouth lineament;	0185, 0187	*in situ* lava flows above precipitous fall in gorge.
	0193	*in situ* lava in gully north of, and parallel to, deep gorge.
	0195D, 0195G, 0195M, 0195T	*in situ* lava flows in northern side of gorge adjacent to precipitous fall.
(b) most of these samples are probably younger than north-south lineament	0175	*in situ* lava at base of gorge.
	0191A	talus, beneath precipitous fall.
	0195U, 0195X	*in situ* lavas in northern side of gorge adjacent to precipitous fall.
4. Summit crater and tholoid	0166	thick flow in western crater wall.
	0170	tholoid lava.
	0171	*in situ* lava, summit of knoll southwest of tholoid.
	0174A	talus, beneath flow in western crater wall.
	0174D	thick flow in western crater wall.

TABLE 3 MODAL ANALYSES OF 21 ROCKS FROM LAKE HARGY AREA

Group	Sample number (prefix 51NG)	volume % phenocrysts					
		Plagio-clase	Olivine	Ortho-pyroxene	Clino-pyroxene	Fe/Ti oxides	Total % phenocrysts
1.	0105A	30	2	-	<1	<1	32
	0106	21	-	<1	-	-	21
	0108	13	3	1	6	<1	23
	0115	13	-	-	-	-	13
2.	0202	25	-	9	4	<1	38
	0201	40	-	1	1	<1	42
	0199	23	-	6	1	<1	30
	0117	41	-	2	1	<1	44
	0205	20	2	9	10	<1	41
	0121	24	1	7	9	-	41
	0209	25	-	1	1	<1	27
	0208	25	-	2	2	<1	29
3.	0122	14	1	3	4*	<1	22
	0123	20	-	2	<1	<1	22
	0198	14	-	1	<1	-	14
	0213	12	-	<1	1	-	13
4.	0110	4	-	1	1	<1	6
	0111	3	-	<1	<1*	<1	3
	0112	3	-	1	1	<1	5
	0113	5	-	1	1	<1	7
	0116	4	-	<1	1	<1	5

* rocks in which rare microphenocrysts of clinopyroxene with a small 2V (0-30°) have been identified; these may be either pigeonite or subcalcic augite (<1% by volume of total rock)

TABLE 4 LOCALITY INDEX FOR SAMPLES OF TABLE 3

Group	Sample	Locality description
1. Tributary of Toiru River	0105A	in situ 2.5 m-wide vesicular dyke; ca. 70 m a.s.l.
	0106	in situ lava flow; ca. 145 m a.s.l.
	0108	in situ lava flow; ca. 280 m a.s.l.
	0115	loose block on caldera rim; ca. 430 m a.s.l.
2. Lobu River section (samples arranged in order from south to north)	0202	in situ lava flow of "remnant block".
	0201	loose block from "remnant block".
	0199	in situ lava flow of "remnant block".
	0117	loose block from "remnant block".
	0205	in situ lava exposures in western
	0121	bank by 1st falls; probably from same flow (compare modal analyses).
	0209	in situ lava; ca. 15 m above western bank.
	0208	in situ lava; ca. 300 m south of 3rd falls.
3. Caldera floor (possibly older flows of Galloseulo)	0122	loose block, western tributary of Lobu River.
	0123	loose block, northeastern shore of Lake Hargy.
	0198	in situ lava exposures in Aburi
	0213	stream and tributary, respectively; probably from same flow (compare modal analyses).
4. Galloseulo volcano	0110	
	0111	loose blocks, streams on western flank.
	0112	
	0113	in situ lava; ca. 785 a.s.l., western flank.
	0116	loose block, stream on southern flank.

TABLE 5 MODAL ANALYSES OF 21 ROCKS FROM SULU RANGE

Group	Sample number (prefix 51NG)	volume % phenocrysts							Total % phenocrysts
		Plagioclase	Olivine	Orthopyroxene	Clinopyroxene	Fe-Ti oxides	Quartz	Amphibole	
1.	0217B	10	4	-	10	<1	-	-	24
	0217E	<1	7	-	6	-	-	-	13
	0217F	2	5	-	7	<1	-	-	14
	2649	31	-	<1	1	-	-	-	32
2.	2650A	8	2	-	<1	-	-	-	10
TALUTU	2651A	11	4	<1	8	-	-	-	23
	2652A	9	5	<1	13	-	-	-	27
3.	2654A	20	<1	4	4	-	<1	-	28
	2654F	20	<1	8	7	<1	-	-	35
4.	3038B	22	-	<1	<1	<1	9	1	32
	3038G	17	<1	2	5	-	-	-	24
	3038H	24	-	<1	<1	1	5	2	32
5.	3024	23	-	1	1	-	-	-	25
	3025B	36	-	<1	-	-	-	-	36
	3028	29	-	2	<1	<1	-	-	31
	3032A	20	-	<1	<1	1	13	2	36
	3032B	20	-	1	2	1	5	-	30*
	3032C	18	-	<1	<1	<1	4	1	23
	3032C'	25	-	5	8	-	-	-	38
	3035	7	1	1	2	-	-	-	10
	3039B	14	1	5	14	-	-	-	33

* includes 1 percent polymineralic grains

TABLE 6 LOCALITY INDEX FOR SAMPLES OF TABLE 5

Group	Sample	Locality description
1. Ruckenberg cone	0217B 0217E 0217F	loose blocks on western flank.
	2649	loose block 3 km northeast of cone; road, ca.750 m north of Malassi village.
2. Talutu cone	2650A	in situ (?) lava, gully on northwestern flank.
	2651A	loose block, gully on southeastern flank.
	2652A	loose block, gully on eastern flank.
3. Malobu cone	2654A 2654F	loose blocks in stream on southern flank.
4. western flank of Sulu Range	3038B 3038G 3038H	loose blocks in prominent gully.
5. coastal exposures	3024	in situ lava flow.
	3025B	in situ lava flow, ca. 3 m thick.
	3028	in situ lava, massive outcrop 5 m high.
	3032A 3032B 3032C 3032C'	loose blocks, up to 2.5 m diameter, on beach.
	3035	in situ lava flow.
	3039B	blocks from in situ lava flow.

Appendix. Aerial photograph index

BAMUS VOLCANO

1. U.S. Army Map Service; all photographs taken at 23,500' above sea-level.

    CPE 7570, Mission 582, Run 53, nos. 39-45 (flown 17 June, 1948).

    CPE 7639, Mission 801, Run 52, nos. 29-34 (flown 4 August, 1948).

    CPE 7656, Mission 926, Run 51, nos. 8-11 (flown 9 August, 1948).

2. QASCO Series, "Central New Britain"; all photographs taken in 1965 at 15,000' above sea-level.

    CAJ 5005, Run 6, nos. 5181-5188.

    CAJ 5005, Run 7, nos. 5197-5207.

    CAJ 5007, Run 8A, nos. 5775-5785.

    CAJ 5005, Run 9, nos. 5261-5269.

LAKE HARGY AREA

1. U.S. Army Map Service; all photographs taken 23,500' above sea-level.

    CPE 7445, Mission 199, Run 49, nos. 4-9 (flown 19 November, 1947).

    CPE 7656, Mission 926, Run 51, nos. 11-16 (flown 9 August, 1948).

2. QASCO Series, "Central New Britain"; all photographs taken 25 August, 1965, at 15,000' above sea-level.

    CAJ 5007, Run 10, nos. 5652-5661.

    CAJ 5007, Run 11, nos. 5628-5638.

    CAJ 5007, Run 12, nos. 5618-5625.

    CAJ 5007, Run 13, nos. 5606-5612.

(Cont'd)

SULU RANGE

1. U.S. Army Map Service; all photographs taken 15 May, 1963.
    Hiran Run 1, nos. 49-53.
    Hiran Run 2, nos. 180-183.

2. QASCO Series, "Central New Britain"; all photographs taken 15 August, 1965, at 15,000' above sea-level.
    CAJ 5004, Run 14B, nos. 4969-4972.
    CAJ 5002, Run 15A, nos. 4779-4780.
    CAJ 5004, Run 16B, nos. 4982-4985.