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Likuruanga Volcano, Lolobau Island, and associated volcanic centres, New Britain: Geology and Petrology

by

R.W. Johnson

LIKURUANGA VOLCANO, LOLOBAU ISLAND, AND ASSOCIATED VOLCANIC CENTRES, NEW BRITAIN: GEOLOGY AND PETROLOGY

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SUMMARY

Likuruanga volcano, the volcanic island of Lolobau, and several associated satellite volcanic cones lie on an east-west line at about 60° to the chain of volcanoes on the mainland of New Britain.

Likuruanga is an extinct volcano, 950m high, with a residual crater breached to the northwest. North of Likuruanga, two dome-shaped satellite centres make up Cape Deschamp and Kakolan Island. The lavas of Likuruanga volcano are basic to intermediate in composition and highly porphyritic; they contain phenocrysts of plagioclase, clinopyroxene, hypersthene, olivine, and iron-titanium oxide, in a groundmass of pyroxene, plagioclase and oxides. Rocks from the core of Likuruanga are extensively propylitized. The rocks of Cape Deschamp and Kakolan Island are more silica-rich than those of Likuruanga: laths of a silica polymorph (tridymite, cristobalite, or both) are present in groundmasses which are deficient in pyroxene. These rocks also contain xenoliths of lava, coarser in grain than the host rocks, and possibly of more basic composition.

Lolobau is a 12km-wide volcanic island, about 20km west of Likuruanga volcano. The center of Lolobau Island is occupied by a caldera, about 5km in diameter, within which several later cones have grown. A fresh-water lake, Namor, is present in the southern part of the caldera. The largest of the post-caldera cones is Lolobau Mountain (829m high) whose products mantle the western caldera rim, and whose summit crater is occupied by Hulu cone. Tobal, Malo, and Sili are three smaller post-caldera cones in the centre of the caldera. Sili is the source of a lava flow which is believed to have erupted in 1905. The relative age of Giwu, the second highest peak on Lolobau in the east of the island, is unknown: it could be a post-caldera cone similar to Lolobau Mountain, but alternatively it may represent an old volcano formed before collapse of the caldera. Banban, Muli, and Tiwongo are volcanic islands west and south of Lolobau Island. The rocks of Lolobau and the off-shore islands range from olivine-bearing basic lavas, through two-pyroxene lavas of intermediate composition, to dominantly glassy pitchstones of dacitic and possibly rhyolitic compositions.

INTRODUCTION

This account is the second of a series of Records that describe the geology and petrology of volcanoes comprising the Bismarck Volcanic Arc. The first report dealt with the active stratovolcano Ulawun (Johnson, 1970). This second report gives an account of the geology and petrology of Likuruanga (North Son) volcano, northeast of Ulawun, and of Lolobau Island, west of Likuruanga (figure 1). Satellite volcanic centres associated with Likuruanga and Lolobau Island are also described. These satellite centres, Lolobau Island, and Likuruanga volcano all lie on an east-west line which probably represents a structural line of weakness at an angle of 60° to the chain of volcanoes on the mainland of New Britain (figure 1).

Employing m.v. "Explorer" as a mobile base, R.P. Macnab, R.J. Ryburn, and the writer examined Likuruanga volcano and Lolobau Island between September 10th and 19th, 1969. Independant field observations were made by each geologist in different parts of the two areas. Thin sections of 148 rocks collected during the survey have been examined by the writer.

LIKURUANGA VOLCANO, AND CAPE DESCHAMP AND KAKOLAN ISLAND SATELLITE CONES

(a) LIKURUANGA VOLCANO

Geology: Likuruanga, or North Son, is the most easterly volcano of the Bismarck Volcanic Arc. The volcano is regarded as extinct as there is no record of eruptions in historic time, no hydrothermal activity is known in the area, and the core of the volcano is deeply dissected. Apart from passing references by Stanley (1922) and Fisher (1939), Likuruanga has not been described previously in the geological literature.

Likuruanga is a steep-sided cone whose base is elongate in a northwest-southeast direction. Its maximum diameter is about 9km, the minimum diameter, in a northeast-southwest direction, is about 7km, and the outer flanks slope at between 17° and 20°.

A deep crater, about 2km wide in a northeast-southwest direction, occupies the central area of Likuruanga. This crater is breached to the northwest, and in plan it is horse-shoe-shaped, with the tips of the "shoe" skewed northwards (figure 2). The highest point on the southern crater rim is 950m.* Beneath the rim, the crater walls are precipitous, but at lower altitudes they sweep down to form a bowl-shaped depression. The crater is drained by a system of steep gullies which join in a single stream draining northwestwards to the sea near Nantambu village. Good exposures of rock from the core of the volcano are found in these gullies. As Likuruanga is everywhere mantled by thick rain forest, exposure elsewhere on the volcano is poor.

On the northeastern flank of Likuruanga, there is a subsidiary conical hill, just over 450m high, which is joined to the main volcano by a low saddle. This subsidiary hill is either a satellite cone that grew on the outer flanks of Likuruanga, or else is an eroded remnant of a volcano (with some signs of a residual crater) produced before the main cone was constructed.

Owing to poor exposure, the structure of Likuruanga is not clearly revealed. However, in stream sections draining the core of the volcano, exposures up to about 400m above sea-level are of dark porphyritic lavas rich in plagioclase phenocrysts. In places, these flows are cut by narrow vesicular dykes and sheets (down to 30cm wide). The intrusive rocks are similar in hand specimen to the lavas, and in many outcrops it is impossible to distinguish between the two. Some exposures reveal fragmental rocks that appear to have been produced by auto-brecciation of lava flows. However, pyroclastic rocks - reworked or primary - appear to be absent from the section examined.

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* This value is from the Department of Forests (Port Moresby) 1:50,000 map "North Son" (1968). The U.S. Army 4" to 1 mile map "Gazelle Peninsula" (1943) gives the height as 3248' (990m).

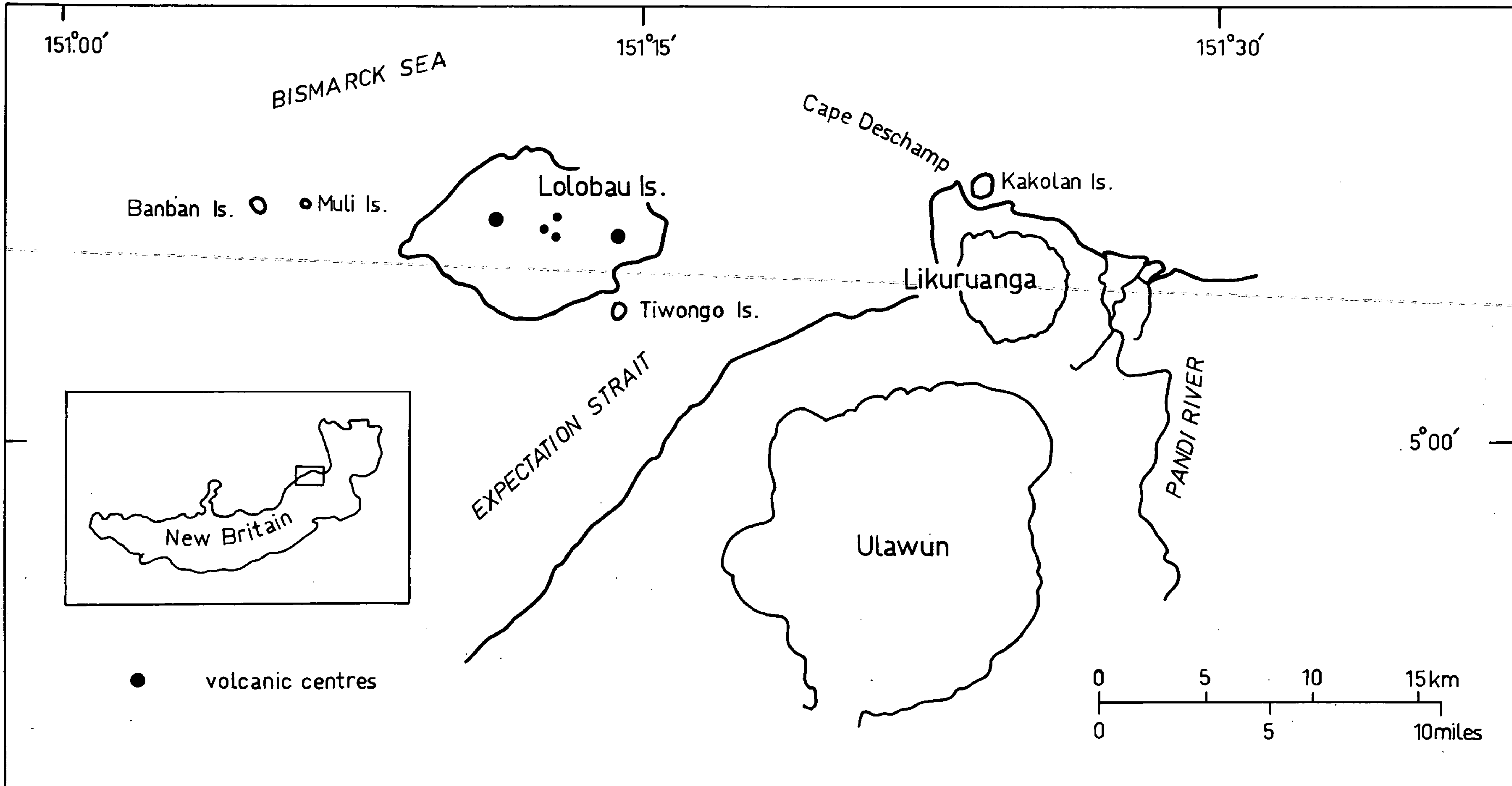

Figure 1. Index map, adapted from U.S. Army 4" to 1 mile maps (1943)

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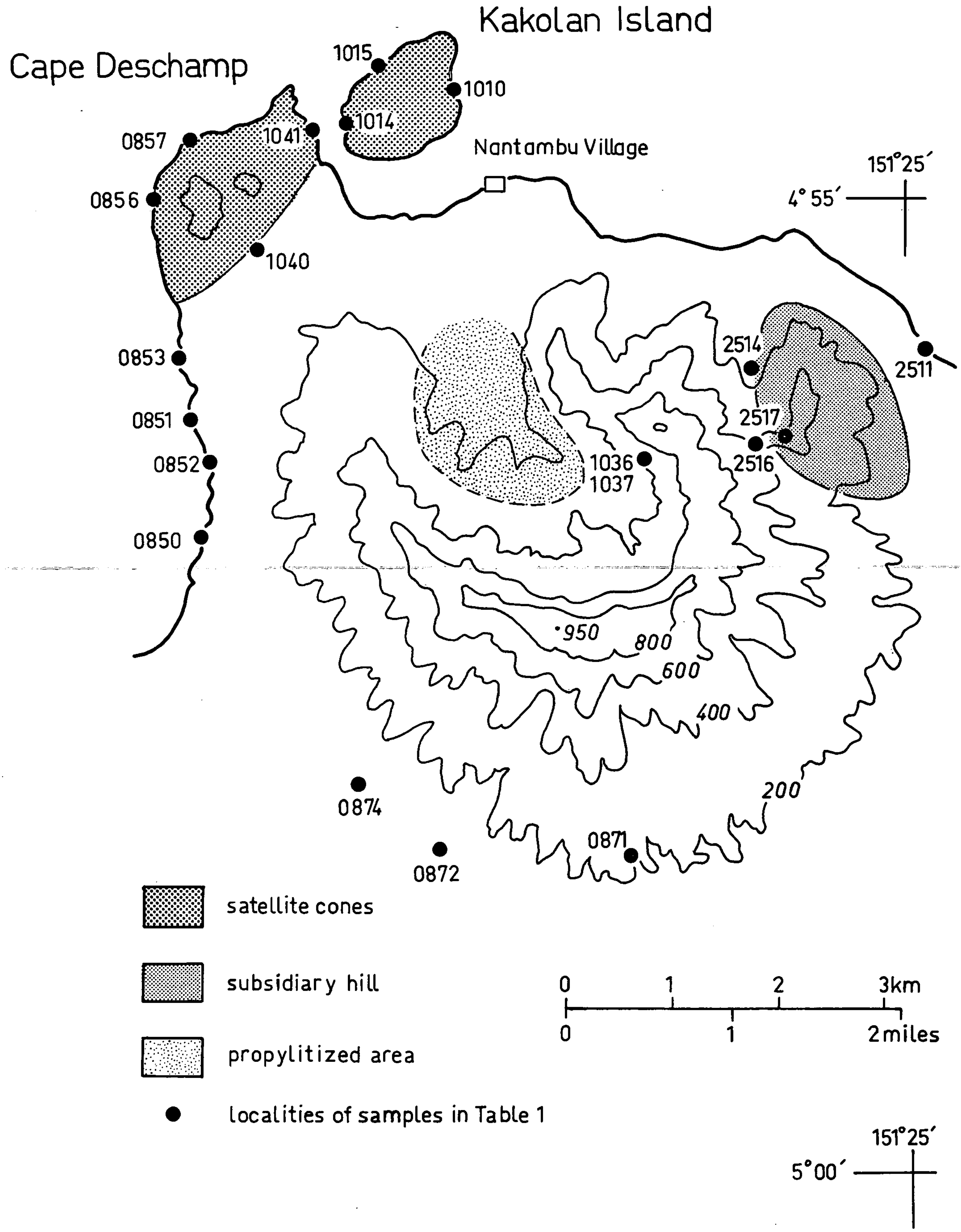

Figure 2. Likuruanga Volcano and associated volcanic centres. Contours (200 metre intervals) adapted from Department of Forests (Port Moresby) 1:50,000 map North Son (1968).

None of the rocks below about 300m in the centre of the volcano is fresh. All the rocks are propylitized, containing abundant chlorite; calcite, chalcedony, and zeolites are also present as amygdale minerals and in the groundmass of the lavas. The approximate extent of the area of propylitization is shown in figure 2. Thermal alteration of the cores of basaltic volcanoes is a well-known phenomenon, and has been well-documented in other eroded volcanoes such as Mull, Scotland (Bailey et al., 1924), and Breiddalur, Iceland (Walker, 1963).

Non-propylitized lava flows crop out at the coast-line, particularly to the south of Cape Deschamp where they are associated with deposits of scoriae. Small outcrops of lava are also exposed on the crest of the subsidiary hill on the northeastern flank of the volcano.

On the southwestern flank of Likuruanga, clay-rich, fine-grained volcanic sediments are exposed in jointed outcrops. In places, pebbles, cobbles and boulders of mostly vesicular lava are included in this deposit which appears to represent deeply weathered outwash material from the higher flanks of Likuruanga. Surface deposits of lapilli found on both the southwestern flank of the volcano and at shore-line exposures are probably young pyroclastic deposits from eruptions of either Ulawun volcano, or Lolobau Island, or both.

Petrography: Sixty-one rocks from Likuruanga volcano have been examined in thin section. They are mostly highly porphyritic lavas containing various proportions of plagioclase, clinopyroxene, hypersthene, olivine, and iron-titanium oxide. These minerals are present either as individual phenocrysts, or as aggregates of phenocrysts.. Modal analyses of 20 Likuruanga samples are given in Table 1. The sample localities of these rocks are described and divided into five geographic groups in Table 2 (see also figure 2).

Plagioclase is the most abundant of the phenocrysts, and it comprises between 9 and 35% of all but one of the rocks listed in Table 1; sample 0872D is unusual in containing less than 1% plagioclase phenocrysts.

Most of the unaltered rocks of group 1C, that is, those above about 350m in the stream section cutting through the propylitized core of the volcano, are characterised by distinctive aggregates of plagioclase which are absent in the rocks of the other groups.

The compositions of feldspars from 6 Likuruanga rocks (determined by the combined-albite twin method) are presented in Table 3. The mean feldspar phenocryst compositions for all six rocks fall in the range An_{71} - $An_{74.5}$ (sodic bytownite).

<u>Clinopyroxene</u>. Augite is the most common pyroxene phenocryst. Grains range up to 5mm in length, twinning is common, and slight compositional zoning is seen in a few grains.

On the basis of the percentage of augite phenocrysts, the 20 rocks of Table 1 may be divided into two groups: those rocks containing 3% or less (mainly less than 1%), and those containing between 7 and 14%. This dichotomy, however, may not be statistically significant, and the fact that none of the Likuruanga rocks in Table 1 appears to contain between 4 and 6% augite phenocrysts may be due merely to sampling bias.

Small, rare (less than 1% of the total rock volume) microphenocrysts of a zoned clinopyroxene with a small 2V and low birefringence are present in some samples, notably in the olivine-bearing lavas of group 1B. This clinopyroxene is probably either pigeonite or sub-calcic augite (see (c) in Table 1).

<u>Hypersthene</u> phenocrysts are present in all but three of the 20 rocks in Table 1. They appear to be most abundant in rocks deficient in olivine phenocrysts. Sample 2511B contains the highest percentage of hypersthene phenocrysts - about 8%. Many hypersthene grains have rims of clinopyroxene (augite) which are mostly developed on the prism faces of the crystals.

Magnesian olivine phenocrysts are present in half of the 20 Likuruanga samples in Table 1, but in 7 of these the amount is 1% or less. Unaltered phenocrysts of olivine are rimmed by fine-grained aggregates of clinopyroxene (probably pigeonite); this indicates that the rocks are silica-saturated, and that the olivine bears a "reaction relationship" with Ca-poor pyroxene. In a few rocks (for example, 0871), outer zones of opaque iron-titanium oxides are developed on the olivine phenocrysts.

In several of the olivine-bearing rocks, the olivine phenocrysts are pseudomorphed - in most cases, completely - by "iddingsite"*. The alteration product is light brown to reddish brown, non-pleochroic, fine-grained, and fibrous. In some rocks, calcite is also present as a major constituent of the pseudomorphs. No rims of clinopyroxene are developed on these pseudomorphed olivine phenocrysts, although in a few cases the embayed outline of the olivine crystals suggests that resorption may have taken place. This observation implies that deuteric alteration of the olivine took place before the olivine had opportunity to react with the liquid to form Ca-poor pyroxene - that is, alteration began at a high temperature. This conclusion does not support the claims of Baker and Haggerty (1967) that (1) "iddingsite" is produced "at low temperature, probably below 140°C", and that (2) it is not "a low temperature analogue of high temperature alteration products..." The Likuruanga rocks suggest that alteration began at high temperature, and that the products could have been "iddingsite"; if they were not "iddingsite", then transformation of a high temperature assemblage to "iddingsite" must have taken place at lower temperatures.

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

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* "a sheet mineral of the chlorite-serpentine group that is intimately mixed with iron oxides in various states of oxidation and hydration" (Fawcett, 1965).

Groundmass mineralogy. The minerals in the groundmass of the Likuruanga rocks are plagioclase, augite, and iron-titanium oxide (probably titanomagnetite, but lath-shaped grains in 1035 suggest the presence of ilmenite); hypersthene, or pigeonite, or both, are also common phases in all of the crystalline rocks. Interstitial glass is common in rocks with a fine-grained groundmass.

The groundmasses of a few samples are particularly coarse-grained, and suggest that the rocks belong to minor intrusions or, at least, to the centres of thick lava flows. In these rocks, cristobalite is commonly present interstitially.

(b) CAPE DESCHAMP AND KAKOLAN ISLAND SATELLITE CONES.

Geology: Light coloured lava flows comprise two satellite cones north-east of Likuruanga. One of these cones forms Cape Deschamp on the mainland; the other one forms the off-shore island of Kakolan (figures 1 and 2).

Kakolan Island is 1.1km wide and rises to 135m above sea-level in the southeastern part of the island. It is fringed by a coral reef for almost its entire periphery. Two gullies, one draining southeastwards, the other northeastwards, radiate from the centre of the island. Exposure is poor in these gullies, and most of the samples from the island were collected from shore-line outcrops. Most exposures are of light-coloured lava, but in places consolidated volcanic rudites, consisting of angular lava clasts with spaces between them are exposed. Dark, basic lava is exposed at the western end of the island.

The Cape Deschamp satellite cone is elongate in a northeast - southwest direction. Its long axis measures 2km, and passes through Kakolan Island when projected northwards, suggesting that eruption from both centres may have been controlled by a fault line running northeast-southwest, parallel to Expectation Strait (figure 1). Cape Deschamp has two peaks, both over 200m high, the higher one in the southeast being 265m above sea-level. The peaks could be the cones of a twin volcano, but alternatively they may represent the erosional remnants of the axis of a single elliptical cone. As in the case of Kakolan Island, outcrops on Cape Deschamp are limited to the shore-line where lavas and associated fragmental rocks, similar to those on Kakolan Island, are found. Both satellite cones appear to be composite, that is, they are not exogenous domes but consist of more than one lava flow, with associated fragmental deposits. The bulbous shape of both cones, however, suggests that the lava flows were less fluid than the basic lavas comprising Likuruanga, and that after eruption they flowed for only short distances from the vent, piling up to form steep-sided cones.

The lavas of both Cape Deschamp and Kakolan Island contain xenoliths of volcanic material slightly coarser in grain than the host lavas, but of similar mineral-content (see following Petrography section). These xenoliths range from microscopic dimensions to sub-rounded clasts about 30cm in diameter. They tend to weather more easily than the lavas, and in many examples they are grey, contrasting with the pinkish hue of the host lava. The xenoliths are interpreted as rocks cooled at depth, and torn from the walls of the conduit during eruption of the viscous lavas..

<u>Petrography</u>: The light colour of the xenolith-bearing lavas from Cape Deschamp and Kakolan Island suggests that the rocks are more silica-rich than those of Likuruanga volcano. This is confirmed by petrographic examination. Twenty-one rocks have been examined in thin section, and the modal analyses of 6 of them are given in Table 1. The localities of these 6 rocks are given in Table 2 and plotted in figure 2.

As in the case of the Likuruanga rocks, the lavas are rich in plagioclase phenocrysts. However, as shown by Table 3, the average feldspar compositions of 3 lava samples are more sodic than those of the Likuruanga lavas, ranging between 62 and 66% (calcic labradorite). Many of the plagioclase phenocrysts in most of the rocks are replaced by "cloudy" fine-grained aggregates of minerals believed to be alteration products. In many feldspar phenocrysts, the core of the crystal is completely replaced, but a clear narrow outer rim of of feldspar remains unaltered. This suggests the alteration of the feldspar phenocrysts may have taken place before eruption, and that in the later cooling history - possibly after eruption - a further rim of feldspar crystallised which escaped alteration.

Augite and hypersthene are also present as phenocrysts. The hypersthene phenocrysts in some of the Kakolan Island rocks are particularly distinctive in displaying opaque rims which grade inward through a dark-brown zone to a highly pleochroic core.

Phenocrysts of iron-titanium oxides comprise between 1 and 2% of the rocks, and are much more noticeable than in the Likuruanga lavas. Many of the oxide phenocrysts appear in aggregates with, or as inclusions in, hypersthene grains. Olivine is absent and, in a few rocks, rare xenocrysts of quartz are found.

The groundmass of the Cape Deschamp and Kakolan Island lavas is distinctive. Apart from a few scattered grains of iron-titanium oxide, the fine-grained groundmass appears to be composed almost exclusively of salic minerals. Groundmass pyroxene phases are deficient and, in many cases, appear to be completely absent. In addition to laths of plagioclase, there are numerous needles of low refractive index and birefringence that are either tridymite or cristobalite (or both)*. Interstitial minerals are of extremely fine grain and low birefringence, and in some cases appear to be isotropic; these minerals may be glass and, possibly, alkali feldspar.

The xenoliths of the Cape Deschamp and Kakolan Island lavas are also light-coloured. To some extent, this is due to the coarse grain, but, as in the case of the lavas, it is due primarily to the high proportion of salic minerals, particularly in the groundmass. However, although the xenoliths appear to be more silica-rich than

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* Sample 0856C was crushed and immersed in oil of refractive index 1.482. Some grains had a refractive index slightly less than 1.482, and others were slightly greater than 1.482. This suggests the presence of both tridymite and cristobalite. An X-Ray Diffraction powder photograph was also obtained for sample 0856C; reflections corresponding to those of both tridymite and cristobalite were revealed.

the Likuruanga lavas, the following mineralogical features suggest that they are more basic than the host lavas: the plagioclase phenocrysts appear to be more calcic(in Table 3, compare the feldspar compositions of sample 0857B, a xenolith, with those of the other samples from group 2A); "iddingsitised" olivine phenocrysts are present; and there is some development of pyroxene phases in the cristobalite-rich groundmass. The xenoliths therefore appear to represent compositions intermediate between those of the Likuruanga lavas and those of the host lavas. A modal analysis of one xenolith (0857B) is given in Table 1.

Seven samples of basic lavas from Cape Deschamp and Kakolan Island have been examined in thin section; they all appear to be identical in mineral-content to the rocks of Likuruanga volcano. Three modal analyses are given in Table 1.

LOLOBAU ISLAND, AND THE ASSOCIATED VOLCANIC ISLANDS OF BANBAN MULI, AND TIWONGO

(a) INTRODUCTION

Lolobau (or Duportail) is a volcanic island 20km west of Likuruanga volcano (figure 1). The island has had a complex volcanic history involving the formation of a caldera in the summit of an old volcano, and the eruption of lava flows and pyroclastic material from at least four later vents inside the caldera. The island is potentially active: there was an eruption of ash and a lava flow early this century, and hydrothermal activity has persisted to present times.

West of Lolobau lie the smaller volcanic islands of Muli and Banban. As Carey (1938) pointed out, these islands, the later cones on Lolobau Island, and Likuruanga volcano all lie on an east-west line, at an angle of about 60° to the chain of volcanoes on the mainland of New Britain (see figure 1). Tiwongo Island is a small satellite cone off the southeastern coast of Lolobau Island.

(b) TOPOGRAPHY OF LOLOBAU ISLAND

Lolobau Island is roughly diamond-shaped (figure 3). It is 12km wide in an east-west direction, 8km wide from north to south, and rises to a maximum height of 829m* at the summit of Lolobau Mountain in the west of the island. A second prominent peak is Giwu (or Gibu), 592m high*, in the eastern part of the island, just east of the highest part of the caldera wall. Coral reefs fringe most of the coast of the island, and there are coral shoals off the southwestern and northeastern shores.

The caldera is mantled by later volcanic products from Lolobau Mountain, and only the eastern part is exposed. The caldera escarpment consists of three more or less straight sections intersecting in a pattern which suggests that the caldera had a quadrate outline; the diagonals of the quadrilateral trend north-south and east-west. The caldera is about 5km from southwest to northeast and its highest point, in the east (immediately west of Giwu), is about 300m above the caldera floor. The escarpment diminishes in height to the northwest and southeast, but continues to be a prominent topographic feature in the southwestern part of the island. The lowest part of the caldera floor is in the south where a fresh-water lake, Namor, 1.5km in diameter at its widest part, is held by the southern wall of the caldera. The lake is separated from the sea by a strip of land only a few hundred metres wide.

Lolobau Island is covered entirely by rain forest, except for two copra plantation clearings - Mauga in the east, and Lolobau in the west (figure 3). A fresh lava flow in the centre of the island appears to be clear of vegetation on air-photographs taken in 1948, but it was covered with a dense growth of young rain forest when viewed in September, 1969. In the summit crater of Lolobau Mountain, areas of stunted vegetation cover (ferns and bracken) are present on Hulu cone and on dormant hydrothermal areas.

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* This value is the metric conversion of an altitude taken from U.S. Army 1" to 1 mile map "Lolobau" (1943).

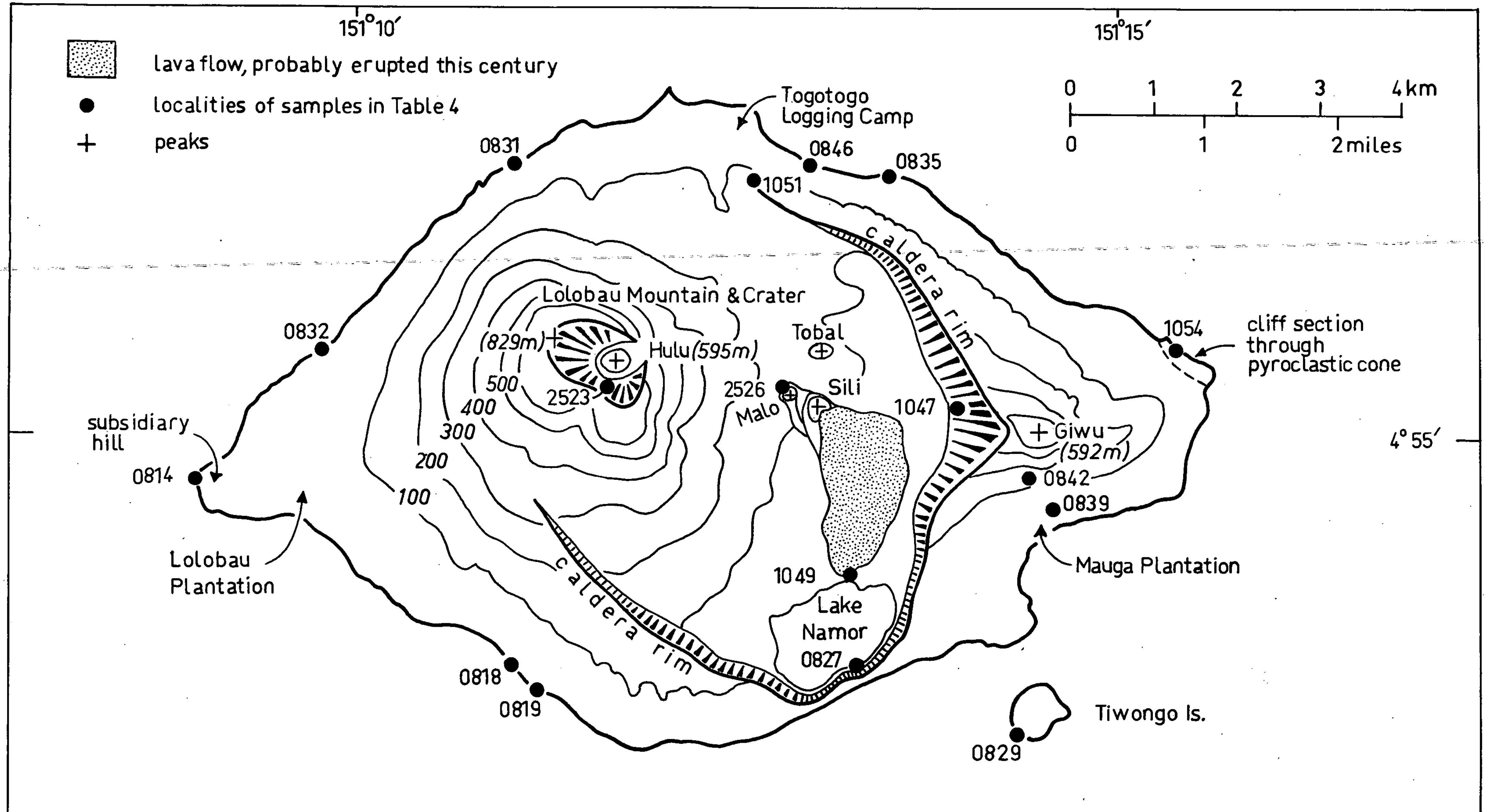

Figure 3. Lolobau Island. Contours (100 metre intervals) adapted from U.S. Army 1" to 1 mile maps (1943)

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(c) PREVIOUS WORK

Lolobau Island was visited by Stanley (1922) who climbed to the southern caldera rim and viewed Lake Namor and the eruptive centres to the north. Brief mention of the island was also made by Powell (1883) and by Carey (1938) in a description of the geomorphology of New Britain. Fisher (1939, 1940, 1957) presented accounts of the geology of Lolobau, and paid particular attention to the economic potential of sulphur deposits in the summit crater of Lolobau Mountain (Fisher, 1942, 1950).

(d) GEOLOGY OF LOLOBAU ISLAND

The oldest part of Lolobau Island appears to be a stratovolcano, elongate in an east-west direction, parallel with the volcanic line between Banban Island and Likuruanga volcano. The summit of the original volcano is now occupied by the caldera. Exposures of the older cone are best developed at the coastline, but outcrops are probably also present in the precipitous eastern caldera wall from which samples of talus have been collected. Lava flows are exposed intermittently at the coast, and they overlie, and are overlain by a variety of pyroclastic materials. Unbedded masses of scoriae, in some outcrops deeply oxidised, are common. Some beds of lapilli and ashes, in various stages of oxidation, are exposed. These show cross-cutting relationships, indicating reworking of air-fall material. Petrographic examination shows that the lava flows of the old stratovolcano are intermediate in composition and contain phenocrysts of plagioclase, hypersthene and augite; phenocryst olivine is rare or absent.

Following collapse of the summit area of the stratovolcano, volcanic activity continued from vents within the caldera. From the evidence of other calderas in New Britain (for example, at Rabaul and the Lake Hargy caldera), it is possible that cauldron subsidence on Lolobau was associated with contemporanous volcanic eruptions, and that the material produced may have been of acidic composition. However, although pumice covers the surface of much of Lolobau Island, it is uncertain how much of it was produced at the time of cauldron subsidence, as it is known that pumice has also been erupted from post-caldera vents.

The largest post-caldera cone is Lolobau Mountain, 829m high, in the western part of the caldera. Its products mantle the western and northern caldera rim. At the summit of Lolobau is a crater, about 1.25km in maximum width, which is breached on its northeastern side; opposite the breach there is a saddle on the southwestern side of the crater rim. The crater walls are steep and heavily vegetated, and no outcrops of rock are visible in them. Talus samples of dark-coloured, porphyritic lavas derived from the crater walls contain prominent phenocrysts of olivine, in addition to those of plagioclase, augite, and hypersthene.

Exposure is also poor on Hulu, a bracken-covered cone that occupies the centre of Lolobau crater. The cone is about 30m high, and a shallow depression at its summit is about 300m across. Limited surface outcrops suggest that the cone is an accumalation of light-coloured pyroclastic material, much of it composed of hydrothermally-altered lapilli.

When Fisher (1942) visited Lolobau Crater in 1937 he observed three areas of hydrothermal activity. One area was on the western flank of Hulu cone, and another was present on the southern inner rim of the crater; both of these areas were "steaming vigorously". A third area of "steaming fumaroles" was observed on the eastern edge of Hulu cone. Fisher also noted extensive surface deposits of sulphur associated with these thermal areas, but commented that the quantity was insufficient to warrant economic exploitation. In June, 1950, Fisher (1950) again visited the crater and reported "...a very marked diminution in the state of activity...Steam is now issuing only very mildly at a few points whereas previously it was given off vigourously over most of the areas containing visible sulphur". It was also observed that, owing to oxidation or erosion, the deposits of sulphur were "restricted to a much smaller area." (Fisher, 1950). R.J. Ryburn visited Lolobau Crater on September 17th, 1969, and observed that there had been complete cessation of hydrothermal activity: there were no fumaroles, no hot soil patches were encountered, and all but a small part of the area on the southern inner rim of the crater was covered by vegetation. Sulphur encrustations were present on the exposed part of the dormant hydrothermal area.

Three minor cones, Tobal, Malo, and Sili (Sile), similar in size to Hulu, are present on the caldera floor east of Lolobau Mountain (figure 3). The 1948 air-photographs show that both Malo and Sili mark the sites of vents which have recently produced southward-flowing lava flows. The latest of these flows issued from a breach in the southeastern side of Sili cone, flowed southwards, and terminated at the present-day north shore of Lake Namor. This flow has edges 10 to 15m high, and on air-photographs prominent flow-lines are visible parallel to the flow edges. In the centre of the flow surface, there are circular collapse holes, and at a point on the eastern side where the flow was scaled, the surface was observed to consist of jumbled tabular slabs of lava similar to "slab pahoehoe" described from basalt lavas in Hawaii (Wentworth & MacDonald, 1953).

Thick deposits of coarse, air-fall pyroclastic material are present close to the three vents in the centre of the caldera. Much of this material is light-coloured pumice lapilli; similar material is also found as a surface deposit on most parts of Lolobau Island. Clasts of dark highly vesicular lava make up Malo Cone, and these are also found within the light-coloured pumice layers suggesting that magmas of two different compositions may have been erupted together. Much of this mantling pyroclastic material must have originated from the Tobal, Malo and Sili vents and, possibly, also from Hulu.

When Stanley (1922) visited Lolobau Island, he noted two of the three minor cones in the centre of the island (presumably Malo and Sili), and reported: "These have been in vigorous eruption lately and are still smouldering." He also viewed the recent lava flow described above: "A recent lava flow, apparently still hot, has been erupted from the larger of the two vents [presumably Sili]..." According to Fisher (1957), the lava flow was erupted from the Sili vent in 1905 at which time Malo was also active. He also states: "Finer fragmentary ejecta were given off at the same time, possibly from Hulu Cone in the main crater..." However, Father J. Stamm who first came to the district in 1914, and is at present in retirement in Rabaul, believes the date of this eruption was 1911, and not 1905 (personal communication, 1969).

Giwu is a prominent volcanic cone in the east of Lolobau Island (figure 3). The age of Giwu is unknown as there is no topographic evidence to indicate whether it formed before or after cauldron subsidence. Fisher (1942) regarded Giwu as post-caldera, and this is supported to some extent by the composition of the lavas which are identical to the olivine-bearing flows of Lolobau Mountain. If Giwu is post-caldera in age then flows which were erupted down the western flank must have spilled over the caldera wall; however, these flows are not preserved, although it is possible that they could have been removed by erosion. The alternative is that Giwu was formed before cauldron collapse, and that the caldera escarpment cut through the western flank of the cone. Dykes are exposed in gullies on the south side of Giwu.

Two other smaller cones are present on Lolobau Island. In the west, a subsidiary hill forms the western tip of the island immediately west of Lolobau Plantation (figure 3). Rare coastal exposures of dark porphyritic lavas are present which are overlain by well-bedded tuffs that appear to be water-laid. At the extreme eastern end of the island, deposits of the second cone are exposed in an impressive vertical cliff section over 30m high and about 600m long, in which is revealed a succession of well-bedded lapillus and ash layers containing dark highly vesicular bombs up to a metre in diameter. Distinctive sedimentary features include: current bedding, cross-cutting relationships, the absence of impact structures beneath the bombs, graded bedding, and a crude imbrication of tabular bombs. No coral, organic remains, or exotic inclusions were found in the succession, and the evidence suggests that the explosive eruptions forming this deposit were subaerial, but that the deposits were extensively reworked. Topographically, the deposits appear to form a low-angle cone. Marine erosion has demolished much of the cone, but the southwestern flanks appear to be preserved immediately southwest of the cliff section.

(e) BANBAN, MULI, AND TIWONGO ISLANDS

Banban and Muli islands lie 7.5km and 5km respectively west of Lolobau Island. Banban is heart-shaped and reef-fringed, and has a dome-shaped profile. Its maximum width is about 800m, and its highest point is 210m above sea-level. Banban is an exogenous lava dome of acidic composition. Exposures at the shore-line and in gullies reveal light-coloured rocks, showing alternating bands of pink and grey, and studded with small scattered phenocrysts, mainly of plagioclase. In places, fragmental textures indicate that some flow-brecciation has taken place. The rock contains xenoliths, up to 2cm in diameter, of lava coarser in texture than the host rock.

Muli is a flat-topped island about 500m in maximum width. It is encircled by an atoll to which it is joined at its southeastern shore. The island is composed of well-bedded layers of dark-coloured lapilli and ash containing some lava blocks rarely greater than about 10cm in diameter. The beds dip to the northwest at a few degrees. The geological significance of Muli Island is uncertain. Two possibilities are that the island is (1) an uplifted block covered by marine volcanic sediments, or (2) a submarine extrusive dome similar to Banban which is mantled by reworked subaerial ejecta.

Tiwongo, about 700m off the southeastern coast of Lolobau Island, is a low-lying thickly timbered island about 700m in maximum width. Coastal exposures are few and consist of dark vesicular, porphyritic, lava. Lava samples from Tiwongo Island show similar mineral-contents to the Banban rocks.

(f) PETROGRAPHY

The rocks of Lolobau and the associated off-shore islands range from olivine-bearing basic rocks through two-pyroxene lavas of intermediate composition, to dominantly glassy pitchstones of dacitic and possibly rhyolitic compositions. Sixty-six rocks have been examined in thin section and the modal analyses of 20 samples are given in Table 4.

All the Lolobau rocks contain phenocrysts of plagioclase and augite, and hypersthene phenocrysts are present in most samples. The basic rocks all contain phenocrysts of olivine. Iron-titanium oxide phenocrysts are common in the acid rocks, and they appear to be absent from some of the basic rocks. Rare microphenocrysts of a clinopyroxene with a small 2V (pigeonite or sub-calcic augite) are present in a few of the olivine-bearing lavas. Aggregates of these phenocrysts minerals are common.

Comparing modal analyses in Tables 1 and 3, the rocks of Lolobau Island appear to be less porphyritic than those from Likuruanga volcano: 60% of the Lolobau rocks contain less than 25% total phenocrysts, compared to only 30% for the Likuruanga rocks. To a large extent this is due to the fact that the acid rocks tend to be less porphyritic than the basic ones, and that there are more acid rocks listed in Table 3 than Table 1. However, the basic-intermediate rocks of Lolobau also seem to contain fewer phenocrysts than rocks of equivalent composition from Likuruanga.

For the purposes of petrographic description, the rocks of Lolobau and its off-shore islands are divided into the following three groups: A, olivine-bearing basic rocks; B, rocks of intermediate composition; C, glassy rocks of probable acid composition.

Group A. Olivine-bearing basic rocks

Rocks containing 1% or more olivine phenocrysts are found predominantly on Gibu Cone and in Lolobau Crater (groups 4 and 5 in Tables 4 and 5). Olivine-bearing lavas are found elsewhere on the island, but these do not appear to be common, and olivine phenocrysts are generally rare; one exception is sample 0827A from the southern wall of the caldera which contains 1% olivine phenocrysts. Olivine phenocrysts are also present in lava clasts from the bedded rudite deposits on Muli Island.

In many of the rocks, particularly those from Gibu Cone, the phenocryst olivine is pseudomorphed by "iddingsite". On many of these pseudomorphs, rims of iron-titanium oxide and an outer zone of pyroxene are developed indicating that oxidation of the olivine to produce oxides and pyroxene must have taken place before formation of the iddingsite. Olivine phenocrysts with a corona of pyroxene only (no iron-titanium oxides) are not common and, in most cases, the pyroxene rim is poorly developed. In none of these examples is the phenocryst olivine iddingsitised. This suggests that the conversion of olivine to iddingsite must have taken place at higher temperatures than that at which olivine reacts with liquid to form Ca-poor pyroxene. This relationship is particularly well illustrated by sample 0839A (Giwu Cone) in which the smaller olivine phenocrysts, which are replaced by iddingsite, have no pyroxene coronas, whereas larger phenocrysts which are not iddingsitised have well-developed peripheral zones of clinopyroxene. The above interpretation agrees with the conclusion reached in the case of iddingsitised olivine phenocrysts in the Likuruanga rocks (page 5).

The compositions of plagioclase phenocrysts from three olivine-bearing rocks are given in Table 6. In two of these, the mean feldspar composition is bytownite, but in sample 2523C it is calcic labradorite. Augite phenocrysts are more abundant in these rocks than those of either of groups B and C. Hypersthene phenocrysts are not common, and phenocrysts of iron-titanium oxides are either rare or absent. Microphenocrysts of clinopyroxene with a low 2V are present in a few samples, but they are always less than 1% by volume. The groundmass phases of the group A rocks are plagioclase, augite, hypersthene, pigeonite and iron-titanium oxides.

Group B. Rocks of intermediate composition

These rocks appear to comprise the bulk of the older part of Lolobau Island (the pre-caldera stratovolcano), cropping out principally at the coastline and in the caldera wall. The rocks appear to be more or less uniform in mineral-content. They are porphyritic, and contain phenocrysts of plagioclase, augite, and hypersthene; olivine and iron-titanium oxide phenocrysts are rare. The mean feldspar phenocryst compositions of two rocks are An75.5 and An74.5 (bytownite; Table 6). Hypersthene phenocrysts are present in all but one of the rocks, and in some samples hypersthene forms distinct monomineralic aggregates. The groundmass minerals are plagioclase, augite, hypersthene, pigeonite, iron-titanium oxides and, in coarsely crystalline specimens, interstitial cristobalite.

Group C. Glassy rocks of probable acid composition.

These rocks are the least porphyritic of the three groups: in Table 4, modal analyses of the Group C rocks show that in all six samples the total phenocryst content is 15% or less, and that they are much less porphyritic than the salic rocks from Cape Deschamp and Kakolan Island. Phenocrysts include plagioclase, augite, hypersthene and iron-titanium oxide. The mean feldspar phenocryst composition of two group C rocks is An 65 (calcic-labradorite) which represents the least calcic of all the feldspar compositions in Table 4. Two pyroxenes, augite and hypersthene, are common to all the samples. Opaque rims are present on the augite and hypersthene phenocrysts of samples from Banban Island, and in this respect they resemble the salic rocks of Kakolan Island and Cape Deschamp. A noteworthy feature of the rocks of group C is that they contain more phenocrysts of iron-titanium oxides than the rocks of groups A and B (up to 1% by volume).

The dominant groundmass phase of these rocks is glass. Several rocks are flow-banded, and there is a wide variation in vesicularity. The glass contains numerous lath-like microlites, most of which appear to be plagioclase; but in several rocks, laths of low refractive index (less than that of the glass and plagioclase) are probably a silica phase (tridymite, or cristobalite or both). Small grains of iron-titanium oxide are scattered throughout, but groundmass pyroxenes appear to be absent. In sample 0819B, the groundmass is distinctive, and consists of optically continuous, monomineralic patches of low refractive index that enclose plagioclase laths and opaque grains; this mineral may be an alkali feldspar.

A distinctive groundmass texture is also found in samples of intra-caldera lavas and bombs (for example, 1049 and 1051). In these rocks, colourless circular areas, up to about 0.1mm in diameter and consisting dominantly of salic minerals (including plagioclase and silica), are enclosed by a darker, more glassy matrix. Grains of iron-titanium oxide are scattered throughout the rocks, but in some samples oxides are concentrated at the edges of the colourless areas.

A few group C rocks contain scattered xenoliths with a coarser grain than that of the host lava. These xenoliths, however, are by no means as large or abundant as those found in the Kakolan Island and Cape Deschamp lavas. The Banban Island lavas, for example, contain xenoliths up to 2cm in diameter. These consist of plagioclase laths, iron-titanium oxide, a few grains of augite and hypersthene (with dark edges similar to the phenocrysts pyroxenes in the host lavas), and abundant interstitial cristobalite.

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TABLE 1. MODAL ANALYSES OF 29 ROCKS FROM LIKURUANGA VOLCANO, AND CAPE DESCHAMP AND KAKOLAN ISLAND SATELLITE CONES

Sample number (prefix: 53NG)	Volume % phenocrysts					
	plagio-clase	Olivine	Hypers-thene	Clino-pyroxene (augite)	Fe/Ti oxides	Total % phenocrysts
0850A	26	-	2	<1	-	28
0850B	25(a)	<1	1.5	<1	-	26.5
0850C	18	-	3	<1	<1	21
0851B	16	-	4	<1	-	20
0852A	27(a)	<1	1	-	-	28
0853A	17	2(b)	4	11	<1	34
0871A	26(a)	1	2	3(c)	<1	32
0871D	19	2.5	1.5	10(c)	<1	33
0871E	10	7	<1	14(c)	<1	31
0872A	34(a)	<1	6	7(c)	-	47
0872D	<1	0.5	1.5	8(c)	<1	10
0874A	17	-	<1	<1	-	17
1036	9	-	-	-	-	9
1037	9	-	2	<1	-	11
2511A	19	1(b)	<1	2(c?)	<1	22
2511B	26(a)	<1(b)	8	12	<1	46
2514A	11	-	-	<1	-	11
2514C	33(a)	-	6.5	1.5(c)	<1	41
2516	10	-	-	<1	-	10
2517	29	-	7	14(c)	<1	50
0856C	22(a)	-	2	6	1	31
0857A	22(a)	-	2	4.5	1.5	30
0857B	25(a)	-	1	4	2	32
1041(d)	24	-	2	5	1	32
1040A	29	1	2	4.5	0.5	37
1040B	35	1	2.5	5	0.5	44
1010B	28	-	1	4	1	34
1015	30(a)	-	1	4	1	36
1014	27	<1	4	8(c?)	1	40

(a) feldspar compositions given in Table 3.
(b) "iddingsited" olivine phenocrysts.
(c) rocks in which rare micro-phenocrysts of clinopyroxene with a small 2V($0-30^{\circ}$) have been identified; these may be either pigeonite or sub-calcic augite (<1% by volume of total rock).
(d) includes quartz xenocrysts (<1% by volume)

TABLE 2. LOCALITY INDEX FOR SAMPLES OF TABLE 1

Group	Sample	Locality description
1A Northwestern coastal exposures	0850A	in situ lava flow.
	0850B	in situ lava flow.
	0850C	in situ lava flow (possibly a dyke rock).
	0851B	in situ lava flow.
	0852A	loose boulder on slope above shore.
	0853A	large boulder, probably close to outcrop.
1B. Southern flank, inland exposures.	0871A 0871D 0871E	loose boulders in stream draining southern slope of Likuruanga.
	0872A 0872D 0874A	loose boulders instreams draining southwestern slopes of Likuruanga.
1C Core of Likuruanga	1036	in situ, possibly from a dyke; ca. 370m a.s.l.
	1037	in situ dyke, trending N95°E; ca. 380m a.s.l.
1D Northeastern coastal exposures	2511A 2511B	beach boulders from eastern extremity of coastal outcrops of Likuruanga rocks.
1E	2514A 2514C	loose boulders in stream on western edge of subsidiary hill.
	2516	loose boulder on ridge joining main cone
	2517	in situ lava from crest and subsidiary hill.
2 Cape Deschamps A. Salic lavas	0856C	in situ lava.
	0857A	in situ lava.
	0857B	xenolith in 0857A lava.
	1041	loose boulders in stream near coast.
B. Basic lavas	1040A 1040B	loose boulders in stream draining both Cape Deschamp and northwestern flank of Likuruanga.
3 Kakolan Island A. Salic lavas	1010B	loose block at coast.
	1015	loose block at coast.
B. Basic lava	1014	in situ lava

TABLE 3

COMPOSITIONS OF FELDSPAR PHENOCRYSTS FROM 10 ROCKS IN TABLE 1

(determined by the combined Carlsbad-albite twin method)

Group Number	Sample Number	Anorthite-content of plagioclase phenocrysts	Arithmetic mean
1A	0850B 0852A	An 67, 83, 82, 67, 70, 78 An 67, 67, 75, 84, 62, 79	74.5 72.3
1B	0871A 0872A	An 73, 76, 81, 68, 74, 59 An 67, 75, 79, 72, 62, 71	71.8 71.0
1D	2511B	An 70, 70, 72, 70, 69, 71, 75	71.0
1E	2514C	An 81, 75, 66, 71, 80, 68	73.5
2A	0856C 0857A 0857B	An 51, 75, 52, 61, 63, 71 An 59, 73, 63, 76, 64, 59 An 79, 69, 76, 82, 77, 68	62.2 65.7 75.2
3A	1015	An 63, 61, 55, 77, 77, 63	66.0

TABLE 4. MODAL ANALYSES OF 20 ROCKS FROM LOLOBAU ISLAND, AND THE ASSOCIATED ISLANDS OF BANBAN, MULI, AND TIWONGO

Group	Sample number (prefix: 53NG)	Petrographic Group	Volume % phenocrysts					total % phenocrysts
			Plagioclase	Olivine	Hypersthene	Clinopyroxene (augite)	Fe/Ti oxides	
1	0814B	B	24	-	7	2	-	33
	0818	B	3	-	0.5	0.5	<1	4
	0819B	C	9	-	1	2	1	13
	1054	B	<1	-	-	<1	<1	ca.1
	0835C	B	25(a)	-	<1	<1	<1	25
	0846	B	2	<1	<1	1	<1	3
	0831	B	27(a)	<1	4	1	1	32
	0832	B	27	-	1	<1	-	28
2	0827A	A	26(a)	1	1	13(c)?	<1	41
	1047C	B	4	-	1	<1	<1	5
	1047D	B	3	-	<1	1	<1	4
3	1049	C	14(a)	-	1	2	1	18
	1051	C	5	-	<1	1	<1	6
	2526A	C	7	-	<1	1	<1	8
4	0839A	A	22	5(b)	<1	5(c)	<1	32
	0842	A	27(a)	4(b)	-	1(c)	<1	32
5	2523B	A	13	1	2	4(c)	-	20
	2523C	A	15(a)	1.5	1	8	-	25.5
6	1058A	C	14	-	<1	2	1	17
7	0829	C	12(a)	-	<1	2	1	15

(a) feldspar compositions given in Table 6.
(b) "iddingsitised" olivine phenocrysts.
(c) rocks in which rare microphenocrysts of clinopyroxene, with a small 2V($0-30^{\circ}$) have been identified; these may be either pigeonite or sub-calcic augite (<1% by volume of total rock).

TABLE 5. LOCALITY INDEX FOR SAMPLES OF TABLE 4.

Group	Sample	Locality description
1 Lolobau Island coastal exposures	0814B	*in situ* lava of subsidiary hill
	0818	clasts derived from volcanic rudites.
	0819B	(as above)
	1054	outer part of bomb in pyroclastic cone.
	0835G	clast in volcanic rudite.
	0846	*in situ* lava.
	0831	*in situ* lava.
	0832	*in situ* lava.
2 caldera wall	0827A	clast derived from volcanic rudite, southern shore of Lake Namor.
	1047C	talus blocks from eastern caldera wall.
	1047D	(as above)
3 caldera floor	1049	edge of recent lava flow from Sili Crater.
	1051	loose block on caldera rim.
	2526A	clast from Malo cinder cone.
4 Giwu Cone	0839A	loose block in gully.
	0842	60cm - wide dyke.
5 Lolobau Crater	2523B	loose blocks from southern part of Lolobau Crater.
	2523C	(as above)
6 Banban Island	1058A	*in situ* lava, gully on east side of island.
7 Tiwongo Island	0829	*in situ* lava at coast.

TABLE 6

COMPOSITIONS OF FELDSPAR PHENOCRYSTS FROM

7 ROCKS IN TABLE 4

(determined by the combined Carlsbad-albite twin method)

Sample number	Petrographic group	Anorthite - content of plagioclase phenocrysts	Arithmetic mean
0835G	B	An 68, 81, 75, 79, 72, 78	75.5
0831	B	An 80, 76, 76, 64, 75, 76	74.5
0827A	A	An 57, 72, 77, 68, 72, 78	71
1049	C	An 69, 61, 66, 69, 62, 65	65
0842	A	An 86, 82, 81, 78, 75, 78	80
2523C	A	An 71, 69, 69, 65, 63, 61	66
0829	C	An 69, 63, 62, 64	65