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Record 1972/133

THE CAPE HOSKINS AREA, SOUTHERN WILLAUMEZ PENINSULA, THE WITU ISLANDS, AND ASSOCIATED VOLCANIC CENTRES, NEW BRITAIN: VOLCANIC GEOLOGY AND PETROLOGY

by

R.W. Johnson and D.H. Blake

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SUMMARY

The following late Cainozoic volcanoes and volcanic centres along the central north coast of New Britain are described:

(1) minor centres in the Cape Reilnitz-Uasilau area;

(2) a cluster of major volcanoes in the Cape Hoskins area, including Pago, an active volcano which was in eruption between 1914 and 1918;

(3) Wulai and Kimbe, small off-shore islands in Kimbe Bay, both of which appear to be the summits of deeply eroded volcanic centres;

(4) Dufaure and Wago volcanoes on the southwest side of Stettin Bay;

(5) Krummel, Garbuna, Welcker, and Bangum volcanoes, which make up the southern half of Willaumez Peninsula.

An account is also given of the volcanic Witu Islands, northwest of Willaumez Peninsula. These comprise:

(1) Unea Island, consisting of remnants of a caldera, and three post-caldera cones;

(2) Garove Island, a central volcano with a steep-sided breached caldera flooded by the sea;

(3) Mundua, Wingoru, Chilling, Wambu, Lumboila, and Undaka Islands, consisting of at least ten minor eruptive centres;

(4) Narage Island, a simple central-type volcano.

Thermal areas are widespread throughout the volcanic areas. The most extensive is in the summit area of Garbuna volcano. Other notable localities are the Uasilau area, Pago volcano and Namagura in the Cape Hoskins area, Narage Island, and areas described by other writers from the vicinity of Talasea and from inside Dakataua caldera in the northern part of Willaumez Peninsula.

The compositions of the volcanic rocks range from basalt (less than 53 wt. percent SiO_2) to rhyolite (more than 73 wt. percent SiO_2), and the most common composition appears to be low-silica andesite (53 - 58 wt. percent SiO_2). The rocks are generally highly porphyritic, with the notable exceptions of most of those from the Witu Islands. The most common phenocryst minerals are plagioclase, augite, and pleochroic orthopyroxene. Also present are phenocrysts of olivine, hornblende, quartz, iron-titanium oxides and, to a much lesser extent, apatite.

The volcanoes overlie the entire known depth range of the New Britain Benioff Zone, and there is a more or less regular variation in chemical composition from rocks of volcanoes in the south (overlying the shallow part of the Benioff Zone), to those making up the volcanoes of Willaumez Peninsula and the Witu Islands (overlying the deeper parts of the Benioff Zone). In particular, the K_2O and total-alkali contents generally increase northwards for rocks with the same silica content. Some lavas on the Witu Islands have much higher TiO_2 and P_2O_5 contents than those on mainland New Britain.

INTRODUCTION

This account is the last of a series of seven Records describing the geology and petrology of Late Cainozoic volcanoes along the southern margin of the Bismarck Sea (see: Johnson, 1970a, c, 1971; Johnson, Mackenzie & Smith, 1970; Johnson, Davies & Palfreyman, 1971; Johnson, Taylor & Davies, 1972). It deals with the volcanoes of the Witu Islands, and with eruptive centres along the central north coast of New Britain west of Sulu Range, including those of the southern but not the northern part of Willaumez Peninsula (Fig. 1). These volcanoes cover an area that overlies the entire known depth range of the New Britain Benioff Zone, which is 70 - 100 km deep in the south and more than 300 km deep in the north (see Johnson, 1970b).

The volcanoes described here were surveyed independently by the writers at various times between 1968 and 1970. During two field seasons in 1968 and 1970, while with the Division of Land Research, CSIRO, Blake mapped the Cape Hoskins area and collected a suite of samples for petrological study (Blake & Bleeker, 1970). In October 1969, BMR geologists, R.P. Macnab, R.J. Ryburn, and Johnson, surveyed all the volcanoes along the north coast of central New Britain, except for (1) those of the Cape Hoskins area, and (2) those at the northern end of Willaumez Peninsula which were described by Lowder & Carmichael (1970) and Lowder (1970). The 1969 BMR survey was undertaken as part of the regional geological mapping of New Britain, and used M.V. 'Explorer' as a mobile base. Geological mapping and sampling of the Witu Islands were completed by Johnson and R.A. Davies (Central Volcanological Observatory, Rabaul) in September 1970, using M.V. 'Kuranda' as a base.

The volcanoes are of considerable interest, and aspects of their geology, volcanic activity, and petrology have been described by several authors. Perhaps the most impressive feature of the area is Willaumez Peninsula, 60 km long, which consists of a series of coalescing volcanoes aligned along a north-south fracture. The Peninsula is at right angles to the volcanic arc that extends along the southern margin of the Bismarck Sea between Rabaul and the Schouten Islands (Fig. 1).

The volcanic rocks range in composition from basalt to rhyolite, and most are richly porphyritic.

Although there are numerous thermal emission points in the area, only one volcano, Pago, south of Cape Hoskins, is known to have erupted this century. It is kept under surveillance by local residents who report anomalous activity to the Central Volcanological Observatory, Rabaul. Eruptions from Pago could have serious effects on the Mosa Oil Palm Development area, the new District Headquarters at Kimbe and other settlements thoughout the Cape Hoskins area, and the Hoskins airstrip.

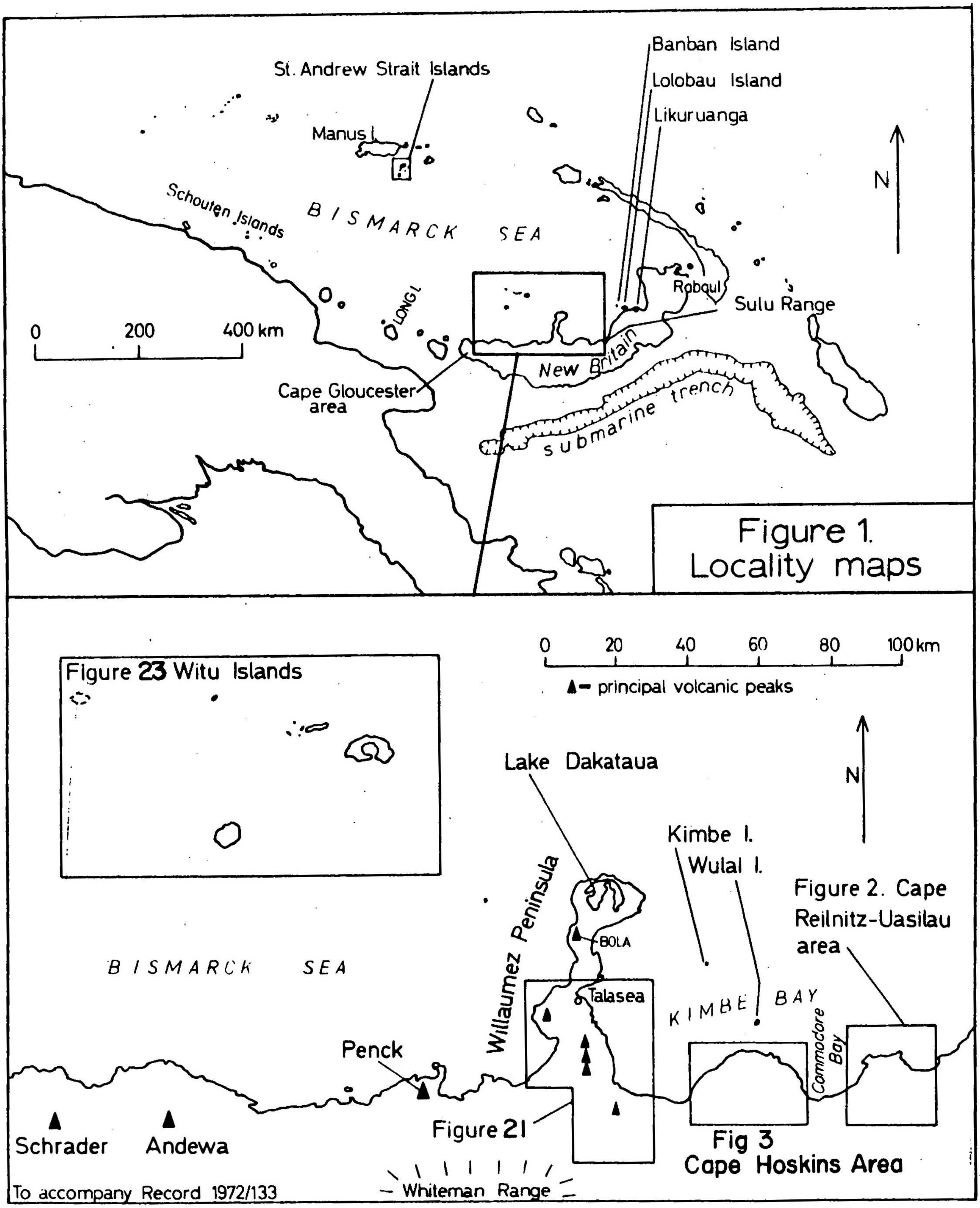
This report is divided into four parts. The first part describes a restricted area of volcanic rocks and associated thermal areas in the vicinity of Cape Reilnitz. In the second part, an account is given of the geology and petrology of the Cape Hoskins area. The third part deals with southern Willaumez Peninsula and related areas, and the Witu Islands are described in Part 4. Johnson is the author of parts one, three and four, and Blake is the author of part two.

The system of rock nomenclature adopted in this report is that of Johnson, Taylor & Davies (1972), who used the following silica ranges as classification parameters:

basalt	$\leqslant 53$ wt percent SiO_2
low-silica andesite	>53 $\leqslant 58$ wt percent SiO_2
high-silica andesite	>58 $\leqslant 63$ wt percent SiO_2
low-silica dacite	>63 $\leqslant 68$ wt percent SiO_2
high-silica dacite	>68 $\leqslant 73$ wt percent SiO_2
rhyolite	>73 wt percent SiO_2

The volcanic rocks range in composition from basalt to rhyolite, the most common rock type probably being low-silica andesite. Most of the rocks are richly porphyritic, but some from the Witu Islands are almost aphyric.

Accounts of the petrology of the various volcanoes and volcanic centres will be given in more detail in later reports, in which chemical analyses will be presented and discussed.



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PART I: CAPE REILNITZ - UASILAU AREA

INTRODUCTION

On the central north coast of New Britain, Late Cainozoic volcanic rocks form a prominent peninsula between Bangula Bay in the east and Commodore Bay in the west, and also crop out south and southeast of Cape Reilnitz towards Uasilau (Fig. 2). Southeast of the peninsula, northeast of Silanga Mission, there are several areas of thermal activity which do not appear to be associated with any obvious eruptive centres.

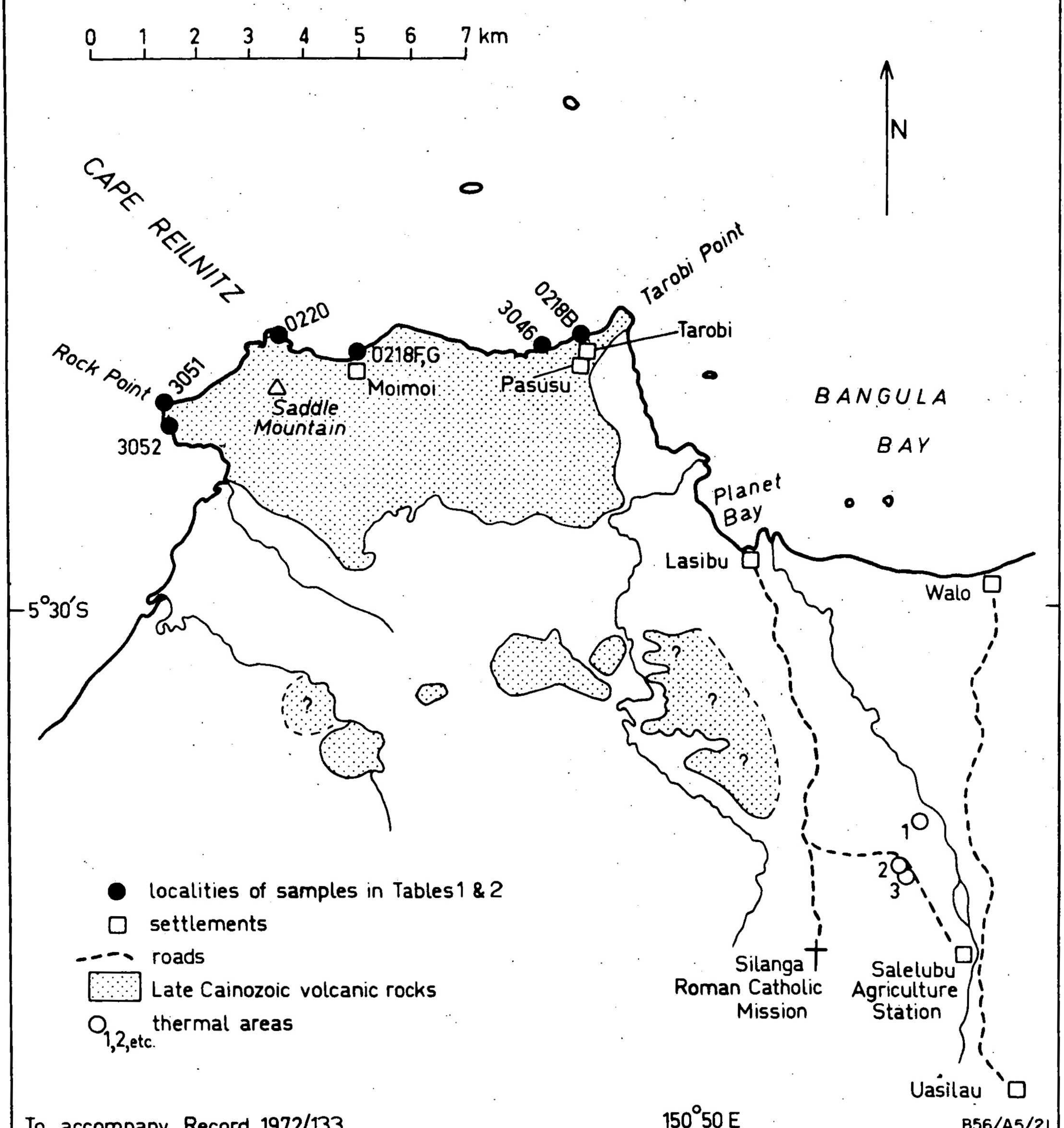
The existence of Late Cainozoic volcanic rocks in the Cape Reilnitz area was not mentioned by earlier writers, although Fisher (1939, 1957) recorded the presence of the 'Walo solfatara field' which is one of several thermal areas in the Silanga-Uasilau area (see also Heming, 1969).

Macnab, Ryburn, and Johnson visited the Cape Reilnitz-Uasilau area on 7 and 8 October, 1969, and examined coastal exposures from Tarobi Point to south of Rock Point. Ryburn also visited two thermal areas northeast of Silanga.

GEOLOGY

Coastal outcrops between Tarobi Point and Moimoi (Fig. 2) appear to be entirely of a wide range of volcaniclastic deposits. Some outcrops are of well-bedded arenaceous deposits which appear to have been laid down in water. Scoriaceous and lapillus layers crop out at other localities, and at least one outcrop is of welded scroiae. Also present are unbedded poorly sorted clastic deposits which were probably laid down by nuées ardentes. In places, as at Tarobi Point, these show vertical columnar jointing.

Figure 2 . Cape Reilnitz - Uasilau area



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Along the coast west of Moimoi there are numerous outcrops of lava. At Cape Reilnitz, a strongly flow-banded lava is exposed, some bands consisting of dark pitchstone. This lava is probably dacitic, and is almost certainly part of a cumulodome that forms Saddle Mountain, the highest point on the peninsula, which rises to 214 m above sea level* about 1 km south of Cape Reilnitz. There are also outcrops of clastic deposits west of Moimoi, including unsorted varieties which may have been deposited by nuées ardentes.

At Rock Point generally massive and fine-grained lava is exposed. It contains olivine phenocrysts, and is probably basaltic. Unlike the flow-banded lava of Cape Reilnitz, the source of this lava is not apparent on aerial photographs.

Some inland parts of the peninsula probably also consist of Late Cainozoic volcanic rocks, but as they are covered by rain forest, they have not been examined. Four of the inland areas seem to have the form of coulees or cumulodomes. Two other areas, however, labelled with question marks in Figure 2, show no obvious constructional volcanic forms on the aerial photographs, and may be outliers of the older Cainozoic formations cropping out in the central parts of New Britain (Ryburn, MacKenzie & Johnson, in prep.).

The volcanic rocks exposed probably range in composition from basalt to dacite.

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* Most of the summit altitude values quoted in this Record are taken from the World Aeronautical Chart 1:1 000 000 map, 'Lae, 2988' (Division of National Mapping, Canberra, 1965) which, in the text, will be referred to as the 'Lae Sheet'.

THERMAL AREAS

Fisher (1957) described a thermal area in the Silanga-Uasilau area (the 'Walo solfatara field') as follows: 'Solfataras and mud springs occur on the coastal flat over an area 25 x 45 m. Steam is given off together with H_2S and probably CO_2. Temperatures range up to 96°C'. Examination of aerial photographs shows that this area, labelled (1) in Figure 2, is the largest of several other thermal points in the vicinity.

In 1969, two hot pools, each 10-15 m in diameter, were located by R.J. Ryburn on the road between Salelubu and Lasibu at points 2 and 3 in Figure 2; these were pale yellow water ponds that emitted water vapour, and gave off a sulphuretted odour. A detailed ground survey of the area would probably find other emission points.

PETROLOGY

Sixteen rock samples from coastal outcrops on either side of Cape Reilnitz have been examined in thin section. Many of these rocks are weathered, and few are suitable for chemical analysis. Some of the samples are of clasts from fragmental deposits, some are of lava flows, and one, 0218F, is a plutonic clast of probable dioritic composition. Modal analyses of five samples, and the sample localities, are given in Tables 1 and 2 respectively.

The rocks show a range in composition from olivine-bearing types which are probably basalts to rocks of andesitic and probably dacitic composition. A chemical analysis of one rock, sample 0208B, shows a silica content of 55.6 wt percent, corresponding to a low-silica andesite composition. The phenocryst content of the samples ranges from less than 1 percent to over 30 percent. The principal phenocryst minerals are plagioclase, augite*, pleochroic orthopyroxene, and olivine.

In the basic rocks, olivine phenocrysts are completely or partly replaced by 'iddingsite'. In a few specimens the olivine has coronas of low-calcium pyroxene. In some rocks, orthopyroxene phenocrysts are rimmed by augite. A glomeroporphyritic texture consisting of augite, orthopyroxene, and plagioclase phenocrysts, similar to that found in some rocks from Sulu Range (Johnson, 1971), is present in sample 3051. Iron-titanium oxide phenocrysts are found only in the less basic rocks. A few samples have grains of quartz rimmed by fine-grained augite.

In the groundmass of most samples, plagioclase, augite, iron-titanium oxides, and orthopyroxene are the most easily recognized minerals. Some samples are flow-banded and extremely fine-grained; others are coarser grained and have more uniform groundmass textures. Low-2V clinopyroxenes** are probably present in the groundmass of most of the basaltic rocks, and have been recognized in sample 3052A. Tridymite and cristobalite are common interstitial minerals. Tridymite forms prominent groundmass laths in a few rocks and is present in some vesicles.

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* Throughout this Record the term 'augite' is used in a general sense for all calcium-rich, iron-poor clinopyroxenes showing moderate 2V (25-60°). It covers the compositional fields of augite (sensu stricto), diopside, endiopside, and salite (Deer, Howie & Zussman, 1966).

** Low-2V clinopyroxenes as referred to here and elsewhere in the text are probably pigeonite or subcalcic augite, but electron microprobe analyses are required to ensure their correct identification, as MacDonald (1968) and Stice (1968) showed that ferroaugites in Samoan lavas also have low 2V.

TABLE 1. MODAL ANALYSES OF 5 ROCKS FROM

THE CAPE REILNITZ AREA

Sample number (prefix 51NG)	Volume % phenocrysts					Total % phenocrysts
	Plagio-clase	Olivine	Ortho-pyroxene	Augite	Fe-Ti oxides	
0218B	<1	-	<1	<1	-	<1
0218G	19	<1	4	7	-	30
0220A	8	-	1	1	1	11
3046	36	2(a)	<1	2	-	40
3052B(b)	2	1	-	<1	-	3

(a) olivine completely pseudomorphed by 'iddingsite'

(b) this sample contains a quartz phenocryst (<1%)

TABLE 2. LOCALITY INDEX FOR SAMPLES OF TABLE 1

AND FOR THOSE REFERRED TO IN TEXT

Sample	Locality description
0218B	boulder near Tarobi lumber jetty
0218F) 0218G)	pebbles on track above Moimoi lumber jetty
0220A	in situ flow-banded lava at Cape Reilnitz
3046	lava clast from unsorted clastic deposit, west of Tarobi
3051	in situ basic lava flow at Rock Point
3052A	in situ lava, south of Rock Point
3052B	beach boulder, south of Rock Point

PART 2: CAPE HOSKINS AREA

INTRODUCTION

Eleven volcanoes ranging in age from mid Pleistocene to Holocene are present in the Cape Hoskins area, on the central north coast of New Britain (Fig. 1). These volcanoes are, in approximate order of decreasing age, Ko, Musa, Kapberg, Busui, Oto, Mululus, Mataleloch, Lolo, Witori, Buru, and Pago (Fig. 3). Pago last erupted in 1914-18 and is the only one that is potentially active. The other volcanoes are extinct and are in various stages of erosion. Details of the volcanoes are summarized in Table 3.

The volcanoes were described in a recent paper by Blake and Bleeker (1970), and these descriptions are summarized here together with a more detailed account of Witori and the results of subsequent laboratory investigations. Of the eleven volcanoes, only Pago has been described previously (Stanley, 1923; Fisher, 1939, 1957). The author visited the area in 1968 and 1970 while with the Division of Land Research, CSIRO. During the 1968 visit a reconnaissance survey of all the volcanoes were carried out with P. Bleeker. Parts of Witori were examined in greater detail during the second visit, which took place after the results of the first visit had been published.

The volcanoes are of the central vent type, and are strato-volcanoes built up of lava flows, pyroclastic deposits and clastic sediments. Extensive ash deposits (tephra) mantle their flanks. The volcanic products are mainly of intermediate and acid composition and are low in potash. Twenty-nine samples have been chemically analysed and the results will be presented in a forthcoming paper (Blake & Ewart, in prep.). Modal analyses of 27 of the chemically analysed samples are given in Table 6.

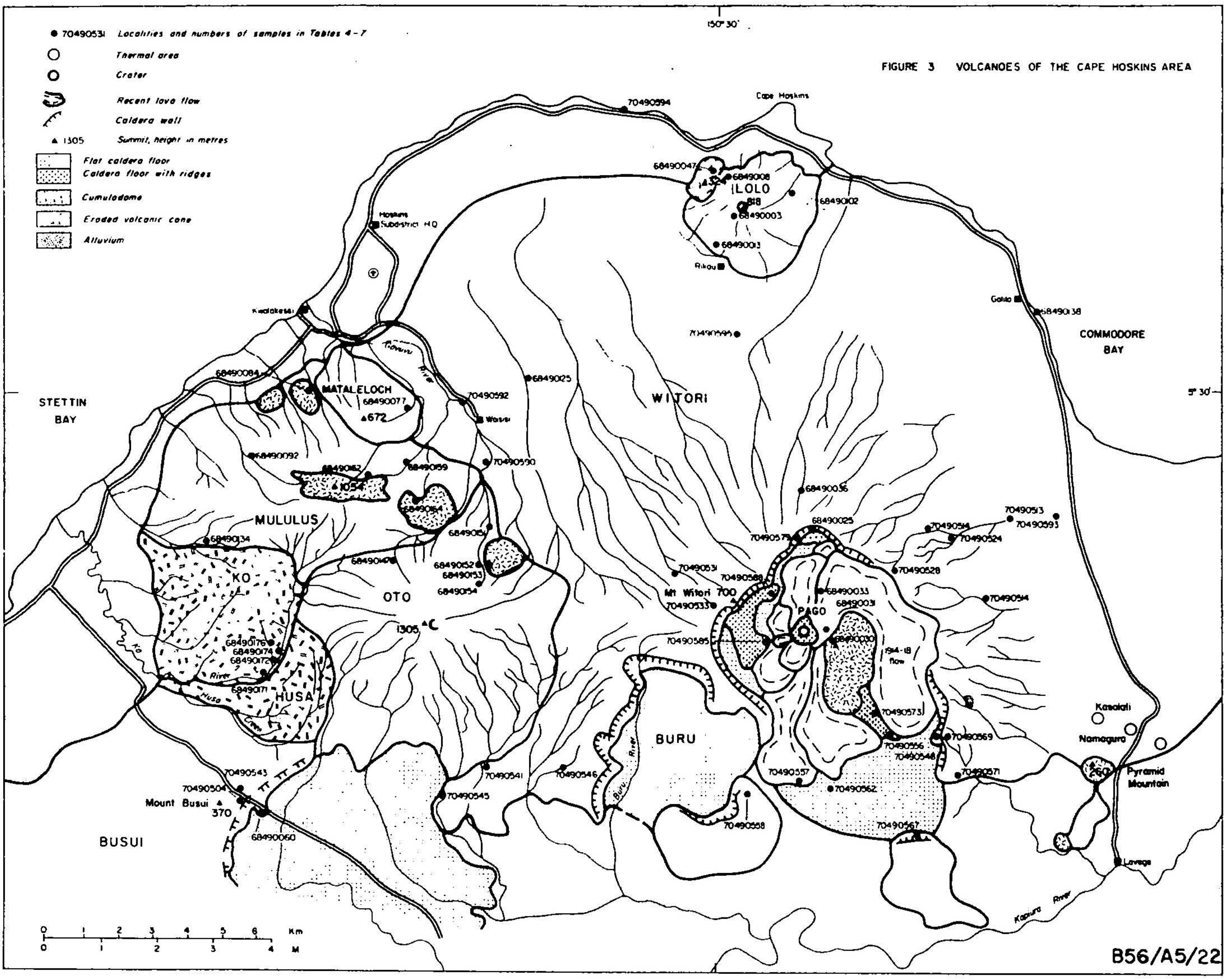

FIGURE 3 VOLCANOES OF THE CAPE HOSKINS AREA

Dense tropical rainforest covers the extinct volcanoes, growing on mostly deep volcanic ash soils, and rock exposures are mainly confined to stream beds, waterfalls and cliffs along incised valleys on the flanks of the volcanoes. Rainforest also covers much of Pago, except for the youngest lava flow and the summit cinder cone, which as yet are only partly vegetated (Paijmans, in press).

The ages of the volcanoes given in this report are based on potassium-argon ages determined by Dr I. McDougall, of the Australian National University, Canberra; on C-14 dates obtained by Dr Kigoshi, of Gakusuin University, Tokyo; on the relationships of the volcanoes to one another; and by comparing the erosional state of the volcanoes with that of Hydrographers volcano of eastern Papua, which became extinct about 650 000 years ago (Ruxton & McDougall, 1967). Like most of the Cape Hoskins volcanoes, Hydrographers is an andesitic stratovolcano that has been eroded under wet tropical conditions. It is in a 'late planeze-early residual stage' of erosion (terminology of Kear, 1957), and has little of its original constructional surface preserved. Potassium-argon and C-14 ages of rocks from the Cape Hoskins area are listed in Tables 4 and 5 respectively.

KO, HUSA, KAPBERG, AND BUSUI VOLCANOES

Geology

The four oldest volcanoes, Ko, Husa, Kapberg and Busui, are in the residual stage of erosion (Kear, 1957), and have none of the original constructional surfaces preserved. Their erosional form indicates that they are probably older than the Hydrographers volcano of eastern Papua.

Ko (or Koa) and Husa were named by Blake & Bleeker (1970) after the main streams draining their flanks. They are steep sided, deeply eroded volcanic cones less than 600 m high situated 20 km west of Pago. The flanks are incised by 'V'-shaped valleys separated by knife-edged ridge crests radiating outwards from the summit areas. Both are probably built up mainly of andesitic lava flows. Ko is partly overlapped by Mululus and Oto, and Husa by Oto and Busui volcanoes.

Potassium-argon ages have been determined on three specimens of lava from Ko (Table 4). They indicate that Ko was active during the late mid-Pleistocene. Husa is probably of similar age.

Kapberg, 16 km northwest of Pago, is a steep-sided serrated cone that is partly overlapped by lava flows from Lolo volcano to the east (Figs 5 and 8). It was called Hapberg by Blake and Bleeker, but Kapberg is now considered to be the correct name (Ryburn et al., in prep.). Lava flows and agglomerate are exposed on the flanks of the volcano, which is in a similar erosional stage to Ko and Husa and is probably of comparable age. The lavas are low-silica andesites.

Busui volcano, situated south of Husa, is named after Mount Busui, 370 m above sea level, the highest point on its flanks. It is a broad low-angle cone of which only the west flank and part of a caldera-like depression to the east are preserved. The west flank is incised by numerous valleys radiating from the caldera rim, which rises up to 70 m above the caldera floor. Busui is probably built up mainly of pumiceous pyroclastic deposits. Such deposits are exposed in gorges incised into the eastern part of the caldera floor. To the north it partly overlaps onto Husa and is partly overlapped by the south flank of Oto. Hence it is younger than Husa but older than Oto.

Petrography

Seven specimens of lavas from Ko, and 3 of lavas and 5 of rock fragments in agglomerate from Kapberg have been examined in thin section. Chemical analyses indicate that the lavas samples from both volcanoes are low-silica andesites. The Ko lavas contain between 8 and 35 percent phenocrysts up to 2.5 mm long enclosed in a fine to very fine-grained groundmass. The phenocrysts,

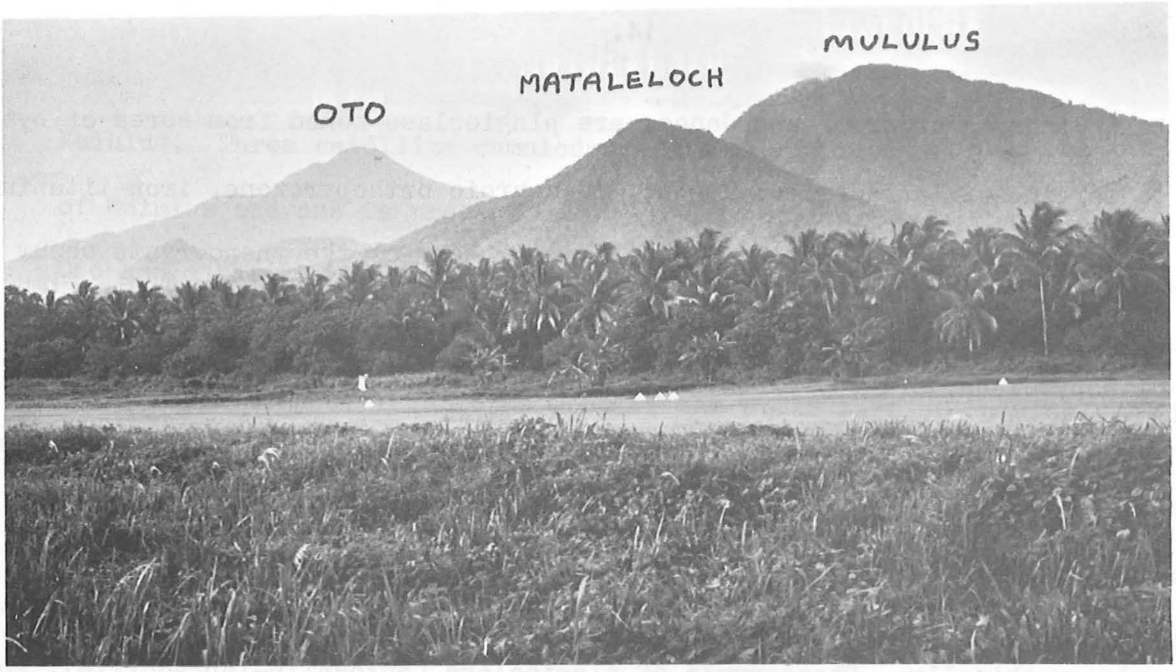

Figure 4. The volcanoes Oto, Mululus and Mataleloch from the north. Hoskins airstrip is in the foreground. Neg. No. L3658-3 (CSIRO)

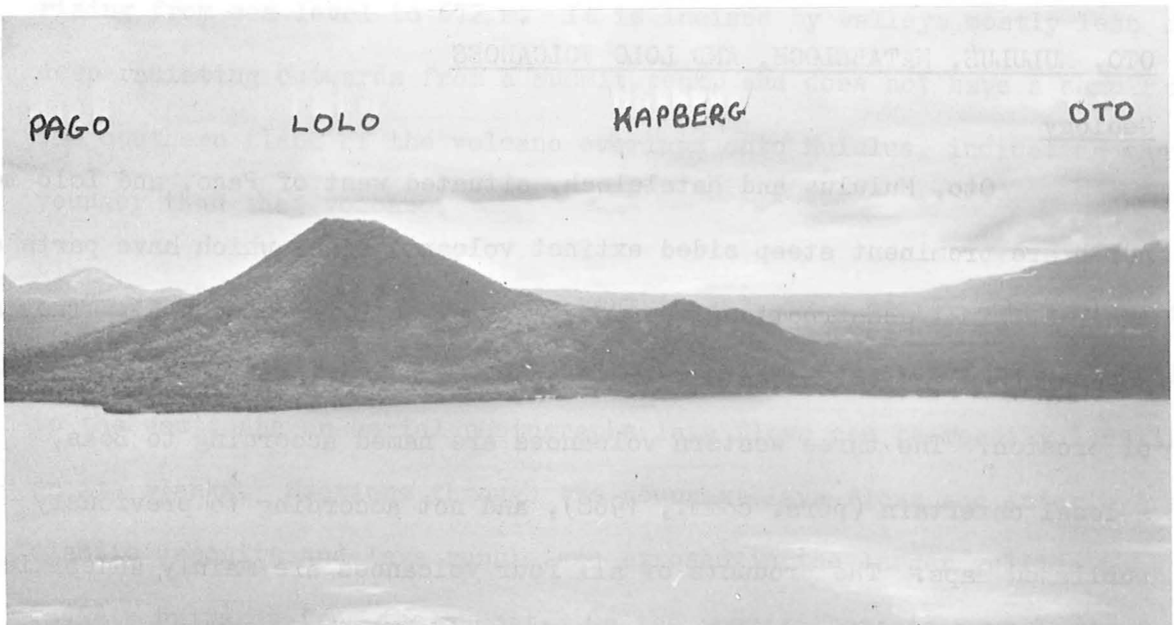

Figure 5. View looking south of the well preserved cone of Lolo volcano and the deeply eroded Kapberg volcano. Pago and the east flank of Oto are visible on the skyline. White patches in the sea are small coral reefs. Neg. No. L3656-8 (CSIRO)

in decreasing order of abundance, are plagioclase zoned from cores of bytownite to margins of labradorite, augite, pleochroic orthopyroxene, iron-titanium oxides, and, in one sample only, olivine. Many of the phenocrysts occur in glomeroporphyritic groups. The groundmass consists of plagioclase, clinopyroxene, orthopyroxene and opaque crystallites and interstitial glass. The crystallites commonly show flow alignment. Tridymite is present in many small vesicles.

Compared with those from Ko, the Kapberg specimens are less uniform petrographically. Phenocrysts of plagioclase (bytownite-labradorite), augite, either orthopyroxene or olivine, and in most but not all specimens, iron-titanium oxides, comprise up to 35 percent of the total rock. Clinopyroxene is more common than orthopyroxene in the groundmass. Biotite crystals are present in the matrix of some of the agglomerate.

OTO, MULULUS, MATALELOCH, AND LOLO VOLCANOES

Geology

Oto, Mululus and Mataleloch, situated west of Pago, and Lolo to the north are prominent steep sided extinct volcanic cones which have parts of their original constructional surfaces preserved (Figs 4 and 5). They are younger than the volcanoes described above, and are in the 'planeze stage' of erosion. The three western volcanoes are named according to Boas, a local chieftain (pers. comm., 1968), and not according to previously published maps. The products of all four volcanoes are mainly andesitic.

Oto and Mululus are the oldest and most eroded of the four volcanoes. Both are incised by radial major valleys over 100 m deep, and by numerous smaller valleys less than 50 m deep. Small planezes are preserved locally, and lava flows on the upper parts of the volcanoes can be recognized on aerial photographs. The two volcanoes are built up of lava flows and clastic deposits, including some containing boulders several metres across. Such boulder deposits are well exposed in streams on the lower eastern flank of

Mululus. Three satellite cumulodomes are present on the lower flanks of Mululus and one is present on Oto. Each dome is less than 400 m high. Oto has a partly preserved summit crater, breached to the east, the top of which is 1305 m above sea-level, the highest point in the area. A massive dome-shaped body of lava forms most of the upper part of Mululus, which rises 1054 m above sea-level.

Potassium-argon ages of two lava specimens from Oto and three from Mululus are given in Table 4. They indicate that both volcanoes are of late Pleistocene age, Oto being active about 190 000 years ago and Mululus 110 000 to 60 000 years ago. Both volcanoes are less eroded than the Hydrographers volcano of eastern Papua.

Mataleloch, on the north side of Mululus, is a symmetrical cone rising from sea level to 672 m. It is incised by valleys mostly less than 30 m deep radiating outwards from a summit peak, and does not have a summit crater. The southern flank of the volcano overlaps onto Mululus, indicating that it is younger than that volcano.

Lolo (or Lollo), on the north coast, is a nearly symmetrical conical volcano rising to 818 m (Figs 5 and 8). It is less eroded than the volcanoes to the west, and on aerial photographs lava flows can be readily identified on its flanks. Sections through the youngest lava flows and interlayered clastic deposits and lava rubble are exposed in the larger gullies that radiate outwards from the summit. On the summit there is a well-preserved crater about 250 m across and 60 m deep. The volcano is in the 'early planeze' stage of erosion and may only recently have become extinct.

Petrography

Sixteen specimens from Oto, 32 from Mululus, 3 from Mataleloch and 16 from Lolo have been examined in thin section. The specimens were collected from lava flows and from boulders in streams and laharic deposits.

Those from Oto range from basalt to high-silica dacite, those from Mululus range from low-silica andesite to high-silica dacite, and those from Mataleloch and Lolo range from basalt to high-silica andesites. Modal analyses of some of the rocks are given in Table 6.

All the specimens contain abundant phenocrysts (up to 38%), generally less than 2 mm across, of plagioclase, augite, and pleochroic orthopyroxene. Most also have iron-titanium oxide phenocrysts and in a few, either or both olivine and quartz phenocrysts are present. Quartz xenocrysts, mantled by augite, occur in one specimen from Lolo and one from Oto. Xenolithic crystal clots are common in lavas from Mululus and are present but less common in lavas from Oto. In all the samples, plagioclase phenocrysts are the most abundant; they mostly have cores of bytownite and oscillatory and normally zoned margins of labradorite. Some augite phenocrysts have cores of orthopyroxene, and prism faces of many orthopyroxene phenocrysts have narrow rims of clinopyroxene. Olivine phenocrysts are most common in lavas from Lolo, where in many cases they are partly altered to iddingsite, and, except in the most basic lavas, are mantled by orthopyroxene.

The phenocrysts are set in a groundmass that is commonly flow-banded and typically consists of plagioclase microlites, minute prisms of either or both clinopyroxene and orthopyroxene, opaque granules, and variable amounts of clear or altered volcanic glass. Clinopyroxene commonly predominates over orthopyroxene in the groundmass of basalt and low-silica andesite, and orthopyroxene predominates in some dacite. Tridymite and less commonly cristobalite are present in many vesicles.

Xenolithic clots in lavas from Mululus and Oto consist mainly of euhedral crystals of plagioclase, pleochroic orthopyroxene, augite, iron-titanium oxides and commonly tridymite and interstitial volcanic glass.

WITORI VOLCANO

Geology

Witori is a stratovolcano made up mainly of dacitic pumiceous deposits and highly vesicular andesitic lava flows. It is a broad low angle cone with a well preserved central caldera within which the active Pago volcano is situated. The volcano is named after Mount Witori, west of Pago, which is about 600 m above sea-level and is the highest point on the caldera rim.

The central caldera is roughly oval and has a scalloped outline. It is breached to the south, where only a small part of the southern flank of the volcano is preserved. The sloping floor of the caldera rises northwards from near sea level to over 200 m, and is bounded to the east, north and west by a caldera wall up to 500 m high. Near the centre of the caldera, partly overlapped by lavas from Pago, a sharply pointed pinnacle rises to about 700 m above sea level (Figs 6 and 11). It has a precipitous west face over 250 m high and a less steep eastern side consisting of two short lobes of lava separated by a knife-edged spur.

The flanks of Witori volcano slope away from the caldera rim mostly at less than 5°. The upper slopes are incised by numerous closely spaced, radially arranged gorges generally over 30 m deep which are separated by knife-edged ridges with precipitous sides (Fig. 6). On the lower slopes the gorges join up to form major flat-floored valleys separated by planezes which have gently undulating surfaces and a variable local relief. The gorges and flat-floored valleys are dry except immediately after heavy rain. To the southwest the flanks are cut off by the caldera-like depression of Buru volcano. Two dome-like hills and three thermal areas are present on the low southeast flank (Fig. 3). The higher of the domes, Pyramid Mountain, rises to 260 m above sea level. The thermal areas have been described recently by Heming & Smith (1968). The main area, known as Nanagura, is shown in Figure 7. It lies between Kasolali thermal area to the northeast (Fig. 10) and a less active thermal area to the southeast (Fig. 9).

The oldest rocks exposed on Witori are lava flows and associated scoria and ash which crop out along the lower part of the caldera wall and in valleys on the upper flank of Oto. The lavas are overlain by pumiceous deposits which are well exposed along the sides of valleys and gorges on the flanks of Witori and also on the upper part of the caldera wall. However, many of the outcrop faces are obscured by landslip material. The thickest succession seen is in the caldera wall north of Pago. Here about 70 m of pumice overlies a group about 200 m thick of highly vesicular dark grey to black lava flows and interlayered scoria and ash. The individual lava flows are mostly less than 10 m thick. Some of the ash beds form hard indurated banded layers and were described as densely welded pyroclastic flow deposits by Blake and Bleeker (1970). Lava flows are also present at the base of the caldera wall southeast of Pago, where some 50 m of lava flows and agglomerate are exposed. The agglomerate is made up of scoriaceous lava fragments and lava bombs, some over 15 cm long, enclosed in a dark ashy matrix. The coarse fragments and bombs make up about 10 percent of the deposit and are arranged in poorly defined layers. The upper 30 m of the 170 m high caldera wall here consists of pumice deposits, but the central part of the succession is obscured by landslips. Similar exposures of lava and agglomerate were seen on the southwest flank, overlain by pumice, but elsewhere on the flanks only pumiceous deposits are exposed.

The two dome-like hills on the southeastern flank are formed of xenolithic lava similar to that found on Mululus volcano.

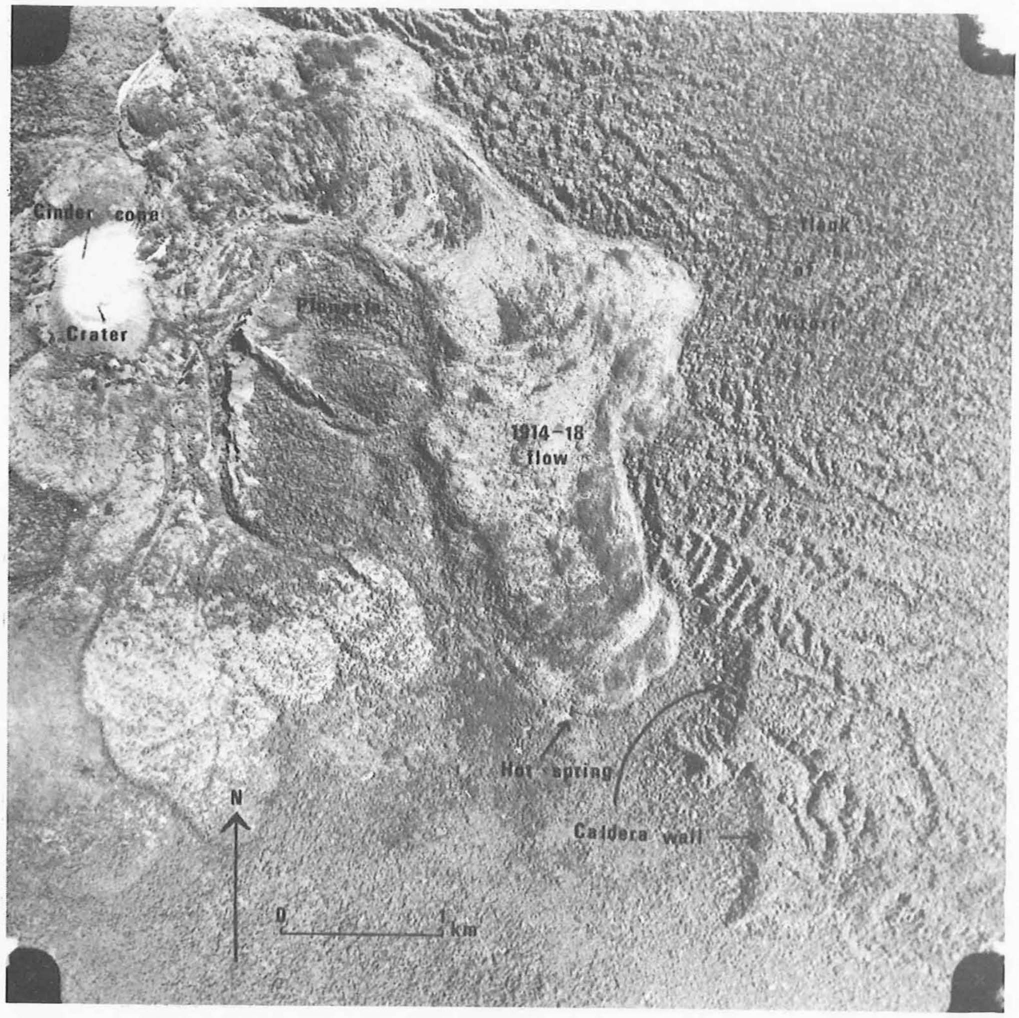

Figure 6. **Vertical aerial photograph taken in 1965 of part of Pago** and Witori volcanoes. The summit cinder cone of Pago and its crater are largely devoid of vegetation, whereas the lava flows show a mosaic of trees and shrubs (dark tones) and grass and ferns (very pale tones). The 1914-18 flow also has small patches of bare rock (pale tone), mainly east-northeast of the pinnacle, where surface features such as lava levees and transverse arcuate ridges and furrows are visible. This flow has partly overtopped the caldera wall of Witori volcano to the east. The pinnacle within the caldera is almost entirely surrounded by younger lava flows from Pago. In marked contrast to Pago, the east flank of Witori is entirely covered by dense forest, and is deeply and closely dissected, although some flat summit surfaces, representing the original constructional surface of the volcano, can be seen preserved in the southeast. CAJ5007-5691.

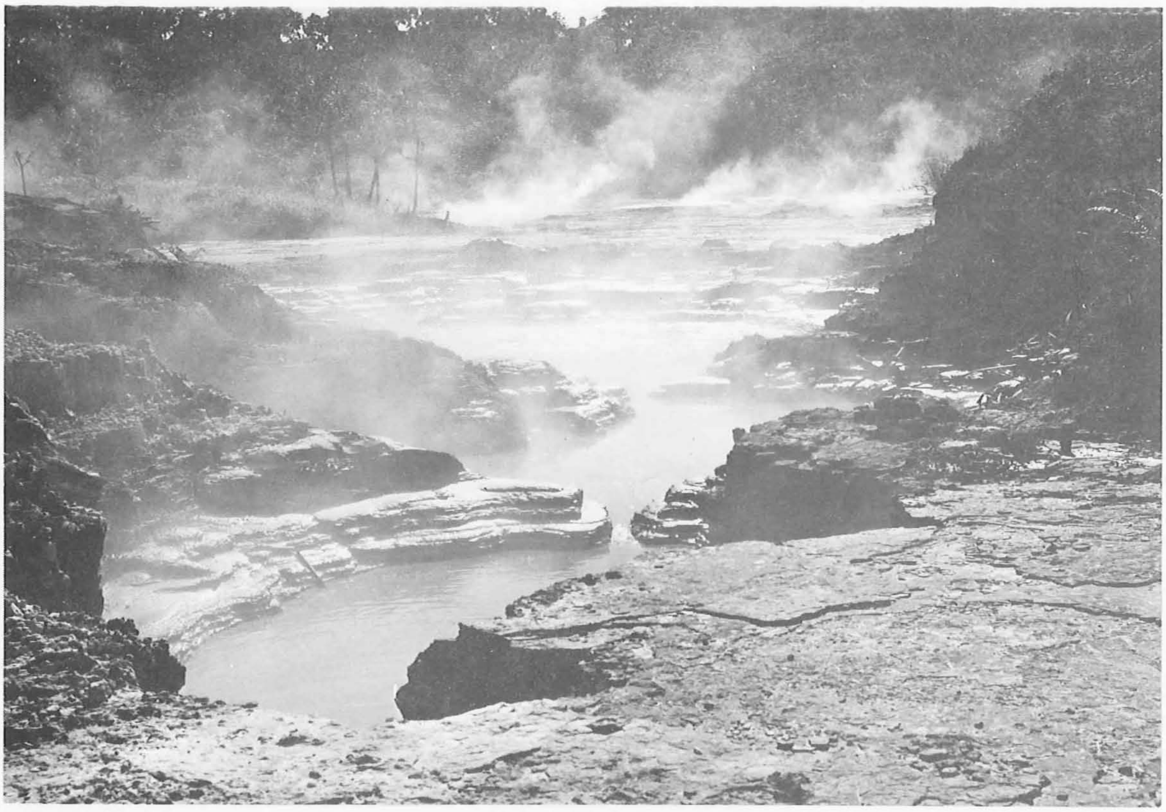

Figure 7. Namagura thermal area. Southeast lower flank of Witori volcano, September 1968. Neg. No. L3661-3 (CSIRO)

Figure 8. View north from the summit of Pago, overlooking the steep side of the 1914-18 lava flow to the east and an older flow to the west, both of which are covered by dense forest. Part of the caldera wall of Witori volcano is shown in the middle distance. The north flank of this volcano descends gently from the caldera rim to Lolo and the much lower Kapberg volcanoes in the background. Neg. No. L3660-7 (CSIRO).

Figure 9. Pool of gently bubbling hot water in front of larger pool of warm water. Thermal area 1 km SE Namagura, southwest lower flank Witori volcano, September 1968. Neg. No. L3674-2 (CSIRO)

Figure 10. Part of Kasolali thermal area, showing a cave that contains boiling mud pools. The bare area round the cave consists of hydrothermally altered rock and small solfataras. Southwest lower flank Witori volcano, September 1968. Neg. No. L3659-5 (CSIRO).

Pyroclastic deposits

The flanks of Witori are formed almost entirely of voluminous pumiceous deposits, laid down mainly by pyroclastic flows but also by air-fall and alluvial processes. Pumice deposits also crop out within the caldera, where they form hillocks, undulating terrain, and, in the northwest, narrow ridges separated by deep very steep sided valleys and gorges. Some of the pumice deposits within the caldera are overlapped by lava flows from Pago.

The pyroclastic flow deposits are composed predominantly of acidic pumice, but also contain up to ten percent by volume of angular andesitic, dacitic, and basaltic lava fragments. Most of the deposits are unwelded, but moderately welded pyroclastic flows are exposed on the northwest and southwest flanks. Blocks of pyroclastic flow material densely welded to obsidian are present both along stream beds and in unwelded pyroclastic flow deposits.

Unwelded pyroclastic flow deposits range in thickness up to more than 30 m. They are formed mainly of pale grey to white pumice fragments and minor lava fragments less than 5 cm across, although larger blocks of lava, some over 1 m across, are present locally, especially in flows exposed on the upper flanks of Witori. Separate flow units are indicated by banding within the deposits. The individual units typically appear chaotic and unsorted and are characterized by an abundance of very fine material. However, some sorting is apparent locally, as large lava blocks, where present, tend to be concentrated in layers and give the deposit a crudely layered appearance (Fig. 13). At several localities bedding and cross bedding are shown by layers and lenses, commonly less than 1 m thick, of partly water-worn coarse sandy to gravelly pumice. The finest and lightest components of the flow deposits were probably removed from these layers and lenses by water during deposition of the pyroclastic flow.

Moderately welded pyroclastic flow deposits are exposed in gorges on the northwest and southwest flanks of Witori, where they grade vertically and laterally into non welded flow deposits. Good exposures occur along the Gavuvu River and its tributaries near Waisisi (Figs 14 and 15), where the welded zone is overlain by over 10 m of non welded pumice. The welded zone is at least 7 m thick, but its base is not exposed.

On the southwest slope, at locality 545, the following sequence is exposed in a vertical cliff section:

Top	Thickness
Inaccessible and obscured by vegetation	about 10 m
Moderately welded part of pyroclastic flow deposit, gradational lower boundary	3 m
Unwelded part of flow deposit	6 m
Tephra layer	0.3 m
Unwelded pyroclastic flow unit	1-6 m
Tephra layer	1.2 m
Group of tephra layers with buried soil on top	2.5 m

Base, 97 m above sea level

The basal tephra layers at this locality show undulating mantle bedding. The buried soil, which contains artifacts consisting of small chips of obsidian and also carbonized wood dated at 2590 ± 250 B.P., indicates that there was a considerable time interval between the deposition of the tephra below and the pumice deposits above. The younger deposits were probably laid down during a single eruptive sequence comprising several separate eruptions, during which the wood in the buried soil was carbonized.
The tephra layers within the younger deposits show layering or 'shower-banding' of the type described from New Zealand (e.g., Cole, 1970). The

moderately welded part of the pyroclastic flow deposit grades laterally into non-welded pumice downstream from this exposure.

The moderately welded pyroclastic flow deposits, unlike the unwelded deposits, are coherent rather than friable, and many of the constituent pumice fragments are flattened and partly moulded around other constituents. This can be seen both in hand specimen and under the microscope. Large lava fragments, some over 1 m across, are present in the moderately welded deposits south of Waisisi. These deposits characteristically show volcano-karst erosion features of the type described by Fairbridge (1968). Fluted gullies (lapies) and small sink holes connecting with underground channels are developed where the moderately welded deposits are exposed in valley floors (Fig. 13), and where they crop out on valley sides they form vertical cliffs below which are strewn large angular fallen blocks. The karst-like features are attributed to the highly porous yet indurated nature of the deposits and the abundance of volcanic acid glass that on weathering is readily altered to clay; such clay is highly susceptible to erosion by solution. The non-welded pumice deposits on Witori do not show the same features because they are highly friable and have little or no secondary clay. It is noteworthy that some of the older tephra deposits on Witori and elsewhere in the Cape Hoskins area are weathered and indurated, and these also show karst-like erosion features.

Fragments of pitchstone representing densely welded pyroclastic flow material are present on the flanks of Witori in pyroclastic flow deposits, in tephra, and as float in streams. They are possibly derived from densely welded deposits within the conduit of the volcano, as no such deposits have been found exposed either on the flanks or in the caldera wall.

Mechanical analyses of several pyroclastic flow deposits and also tephra were carried out for the author by B.G. Griffiths at the

Division of Land Research, CSIRO. Following Walker (1971), the two parameters chosen to quantify the main characteristics of each cumulative curve are the median diameter Mdϕ and the deviation or sorting coefficient $\delta\phi$ of Inman (1952), where d is the diameter in millimetres and $\phi = \log_2 d$. The two parameters for the samples analysed are given in Table 7, together with the median diameters in millimetres. Plots of $\delta\phi$ against Mdϕ are shown in Figure 17, which is based on Figure 2 of Walker (1971). The sorting coefficients of the pyroclastic flow deposits are higher than those of the tephra and confirms their general lack of sorting. Figure 15 shows that most of the analysed samples of pyroclastic flow deposits and tephra fall within the respective fields determined by Walker.

Loose unconsolidated tephra consisting of pumice and subordinate lithic fragments is preserved on ridge crests and planezes on the flanks of Witori, and indurated tephra underlies some of the pyroclastic flow deposits lower down in the flank succession. Buried soil horizons are present within most of the tephra sequences. The lithic fragments in the tephra are similar to those in the pyroclastic flow deposits. Rare vesicular bomb-like lava fragments are present in some tephra layers. The tephra is made up of fragments which range in grainsize from silt to coarse gravel but most are less than 2 cm in diameter. Individual beds are mostly less than 50 cm thick. They show undulating bedding, as they mantle the pre-existing topography, and commonly show internal 'shower-bedding'. The tephra generally has a lower sorting coefficient than the pyroclastic flow deposits (Table 7, Fig. 17). Indurated tephra underlies pyroclastic flow deposits on the northwest flank of Witori, near Mataleloch. It includes thin interbeds of dark grey non pumiceous tephra. The indurated pumiceous tephra is yellowish rather than pale grey and the original pumice glass is mostly or completely altered to clay minerals.

The thickest tephra layer on Witori is on the north and east flanks (Fig. 16), overlying the youngest pyroclastic flow deposit. It extends from the caldera rim, where it is about 5 m thick, to coastal cliffs 3 m high east of Lolo, where it is about 2 m thick. On the coast, the tephra overlies a buried soil containing charcoal fragments dated at 1590 ± 300 years B.P., whereas near the caldera rim it overlies a buried soil containing charcoal dated at 1530 ± 100 years B.P. This tephra layer was described as a probably pyroclastic flow deposit by Blake & Bleeker (1970), but as, unlike most flow deposits, it lacks fine material and is formed almost entirely of coarse pumice, it is now thought more likely to be an air-fall deposit. Some pumice fragments within it are more than 25 cm across, even on the coast 10 km from the caldera. The coarsest pumice fragments within this deposit typically have pinkish interiors. Similar pumice fragments were recorded by Williams (1942) in tephra from Mount Mazama, Oregon, and he attributed the pink colour to atmospheric oxidation of iron-bearing gases; small fragments did not become pink as they chilled more rapidly and ceased almost immediately after eruption to give off gas.

Alluvial deposits are present on the floors of the incised valleys on the flanks of Witori, where they locally form terraces up to 3 m high. They are also present on the caldera floor, and underlie tephra and pyroclastic flow deposits on the lower flanks. The alluvial deposits consist of waterlain and commonly cross-bedded coarse to fine pumiceous sand and gravel and also gravel formed mostly of lithic fragments. Buried soil horizons are present in some of the deposits, as at locality 68490125 on the lower northwest flank, where two such horizons occur at 56-74 cm and 240-253 cm below the top of a terrace 3 m high. Charcoal fragments in the upper soil have been dated at 1190 ± 90 years B.P. and similar fragments in the lower soil have been dated at 1740 ± 100 years B.P.

Eruptive history

In its initial stages Witori volcano was built up mainly of andesitic lava flows that probably formed a steep-sided cone similar to most of the other volcanoes in the Cape Hoskins area. Later an abrupt change in the type of activity occurred, and subsequent eruptions consisted of explosive activity accompanied by the emission of pumiceous pyroclastic flows and tephra, but not lava flows. The caldera probably formed during a major catastrophic eruption towards the end of this phase, when the welded pyroclastic deposits on the northwest and southwest flanks and the thick air-fall layer on the north and east flank were laid down. The pumice forming hills and ridges on the caldera floor may have been deposited during later stages of the same eruption. Post-caldera activity included the eruption of highly viscous dacitic magma to form the prominent pinnacle inside the caldera. Subsequently, a series of lava flows were erupted within the caldera of Witori to form Pago volcano.

Dates obtained on charcoal collected from buried soil horizons on the flanks of Witori are given in Table 5. The ages given by charcoal beneath the partly welded pyroclastic flow deposit on the southwest flank and beneath the thick coarse tephra layer on the coast east of Lolo indicate that the caldera-forming eruption probably took place about 2600 years ago. If this interpretation is correct, the date of 1530 $\pm$ 100 years B.P. for the charcoal beneath the thick tephra near the caldera rim at site 70490528 is anomalous. This charcoal, which was collected from a cliff exposure at the head of a gully, may represent tree roots charred during a later eruption.

When the caldera eruption took place, pumice deposits probably blanketed the flanks of Witori, partly or completely filling pre-existing valleys. If such was the case the incision of the present valleys on the flanks did not begin until after the caldera eruption. The dates obtained on charcoal from the buried soils in terraces on the northwest flank indicates that the incision reached its present level about 1750 years ago.

The age of 9460 ± 150 years B.P. on charcoal collected from cliffs on the coast north of Lolo may date an earlier eruption from Witori. The buried soil containing the charcoal underlies nearly 5 metres of bedded and cross-bedded water-lain pumiceous sand and gravel. The nearest source for the pumice is Witori volcano.

Petrography

Most of the lava flows underlying the pumice deposits on Witori are high-silica andesites. They contain phenocrysts generally less than 1 mm long of plagioclase (bytownite cores and labradorite margins), augite, pleochroic orthopyroxene and sparse iron-titanium oxides enclosed in a very fine-grained and partly glassy groundmass. Partly resorbed quartz 'xenocrysts' are present in some specimens. The lava flow at the base of the succession exposed in the northern caldera wall is a low-silica andesite (sample no. 68490025) consisting of plagioclase phenocrysts, similar to those in the high-silica andesites, and microphenocrysts of plagioclase, augite and opaques, but not orthopyroxene, set in a mostly glassy groundmass. This low-silica andesite is characterized by small globular vesicles whereas the high-silica andesites have highly irregular lens-like vesicles.

The pinnacle inside the caldera is formed of high-silica dacite (sample no. 68490030) containing small phenocrysts enclosed in a very fine-grained flow-banded groundmass consisting of plagioclase laths, clinopyroxene and orthopyroxene crystallites, opaque granules and interstitial glass or altered glass.

Specimens collected from the domes on the southeast flank are dacite consisting of phenocrysts of plagioclase (normally zoned from bytownite to labradorite), augite, pleochroic orthopyroxene, iron-titanium oxides, and quartz set in a groundmass of devitrified glass. The dacite contains xenolithic clots made up of plagioclase, augite, pleochroic orthopyroxene, tridymite, quartz and opaque crystals.

Over 100 samples of pumice from pyroclastic flow and air fall deposits on Witori were examined microscopically to determine the phenocryst minerals and the refractive indices of the acid glass, as it was hoped that these would serve to distinguish the various pyroclastic deposits from one another and hence be an aid in correlation. However, this proved unsuccessful, as the internal variation within most of the deposits covers the range between different deposits. All the samples of pumice examined contain euhedral phenocrysts of plagioclase, pale green augite, pleochroic pale pink to very pale green orthopyroxene and iron-titanium oxides. Green or brown hornblende is present as phenocrysts in some samples, as also is quartz. In addition a few samples contain rare crystals of olivine and one has crystals of biotite. Augite, hypersthene and magnetite are commonly present in roughly equal proportions. Hornblende, where present, is generally subordinate to pyroxene but in some samples is the dominant ferromagnesian mineral. The phenocrysts are enclosed in highly vesicular glass which under the microscope is seen to be clear and generally colourless when fresh, though in some samples some clear pale brown glass is also present. Very rarely the glass contains minute microlites, possibly of feldspar.

Refractive indices of the fresh pumiceous glass range from 1.498 to 1.518 but mostly fall into two groups, 1.500-1.504 and 1.510-1.514. These indices indicate that the pumice is probably dacitic, with silica contents between 65 and 70 wt percent (Huber & Rinehart, 1966). On weathering, the pumiceous glass becomes turbid due to the development of clay minerals, and has a higher refractive index. Also, unlike fresh glass, which is isotropic, turbid pumice is faintly birefringent.

In the pumice from moderately welded pyroclastic flow deposits augite is generally subordinate to hypersthene, and minor hornblende and sparse quartz are commonly present. The refractive indices of the pumiceous glass are mostly in the range 1.502 to 1.512.

The pumice in the thick tephra layer on the north and east flanks contains phenocrysts of plagioclase and roughly equal porportions of augite, pleochroic orthopyroxene and iron-titanium oxides in pumiceous glass that mostly has a refractive index in the range 1.512-1.516. Minor hornblende and quartz phenocrysts are present in a few samples.

The lithic fragments in the pyroclastic deposits are mostly of high and low-silica andesite and dacite similar petrographically to the lavas of Witori and Oto. Less common pitchstone fragments, derived from densely welded pyroclastic flow deposits, contain scattered euhedral to fragmentary crystals mainly less than 1 mm long of plagioclase (mainly labradorite), pleochroic orthopyroxene, augite, opaques and, in some cases, hornblende and quartz, together with lithic fragments. These are enclosed in a eutaxitic groundmass consisting of clear colourless to pale brown glass formed of flattened pumice fragments. The only pitchstone sample which has been chemically analysed, specimen no. 68490036F, is a rhyolite containing 75 wt percent silica.

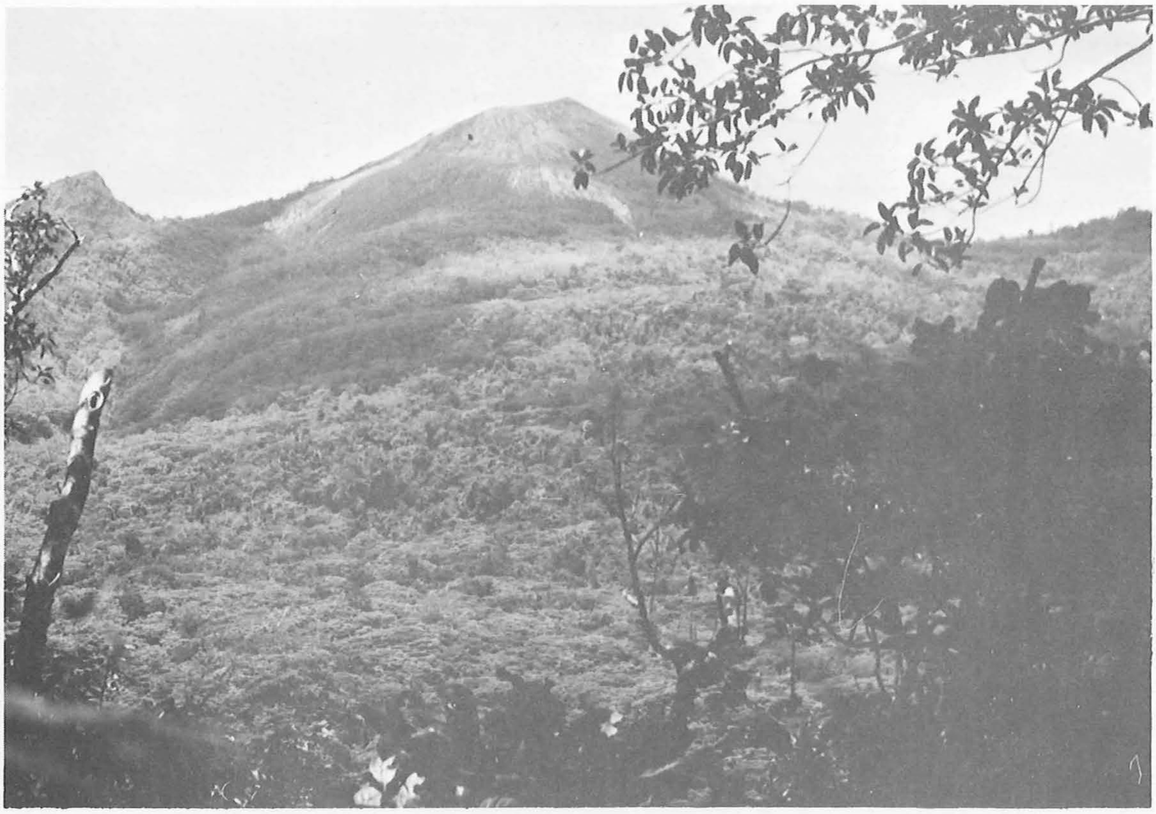

Figure 11. Pago from the caldera wall of Witori to the north-northwest, showing the summit cinder cone and a densely forested pre 1914 lava flow. The 1914-18 lava flow, also covered by forest, is visible on the extreme left, between the cinder cone and the pinnacle to the east. Neg. No. L3656-10 (CSIRO).

Figure 12. Steam rising from a hot spring and swamp at the toe of the 1914-18 lava flow from Pago volcano, August 1970. Neg. No. L4143-4(CSIRO).

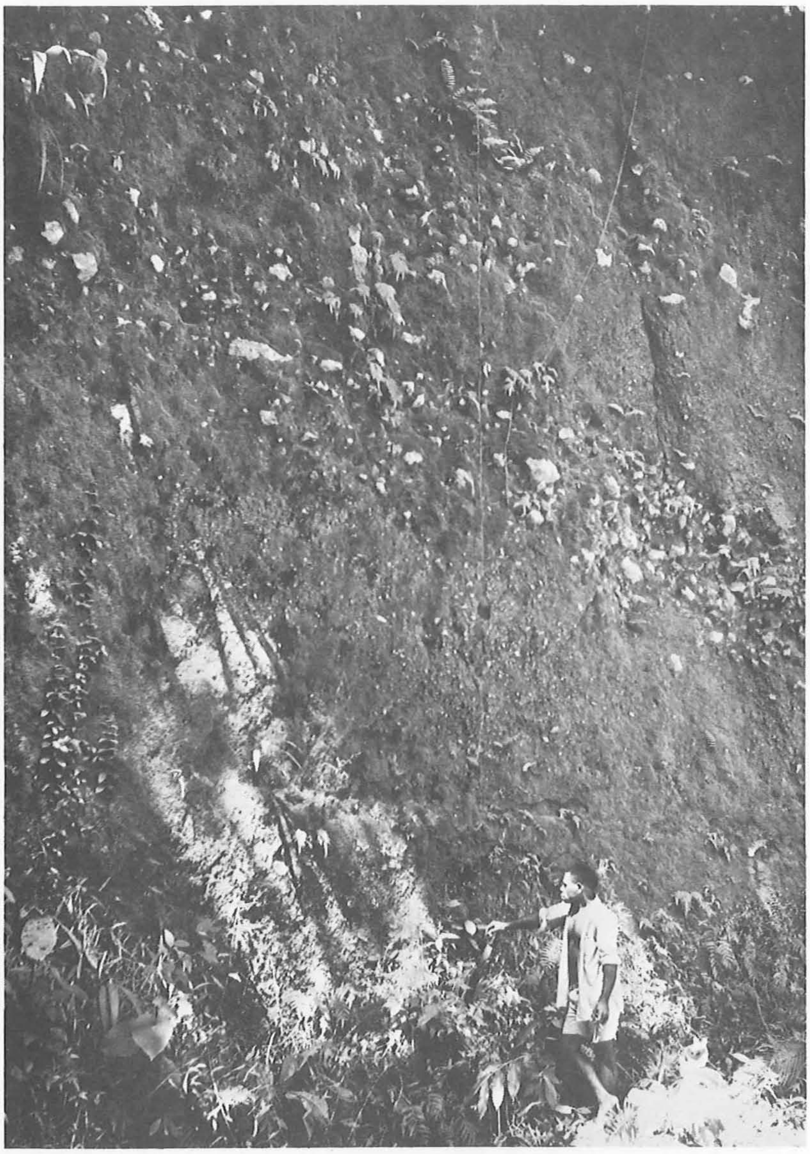

Figure 13. Blocks of lava forming crude layering in a pyroclastic flow deposit consisting mainly of pumice. Site 70490514, northeast lower flank of Witori. Neg. No. L4138¢10 (CSIRO).

Figure 14. Volcano-karst. Narrow gully (lapie) with fluted sides eroded in a moderately welded pyroclastic flow deposit near Waisisi. Site 70490590, northwest lower flank of Witori. Neg. No. L4194-8 (CSIRO).

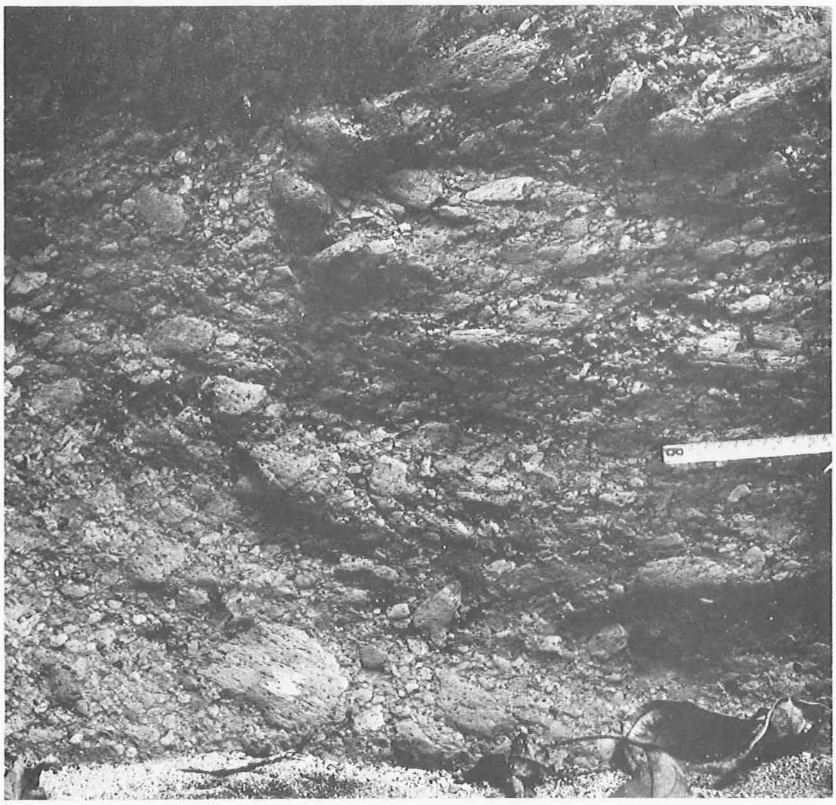

Figure 15. Moderately welded pyroclastic flow deposit, containing large blocks of pumice, exposed in fluted side of gully. The scale shown is 12 cm long. Near site 70490590, northwest lower flank of Witori. Neg. No. L4195-3 (CSIRO)

Figure 16. Coarse pumiceous tephra (pale) overlying a buried soil horizon (dark) developed on banded pumice that is probably the upper part of a pyroclastic flow deposit. The tephra is the youngest thick deposit on the east flank of Witori. Site 70490513. Neg. No. 4138-3 (CSIRO).

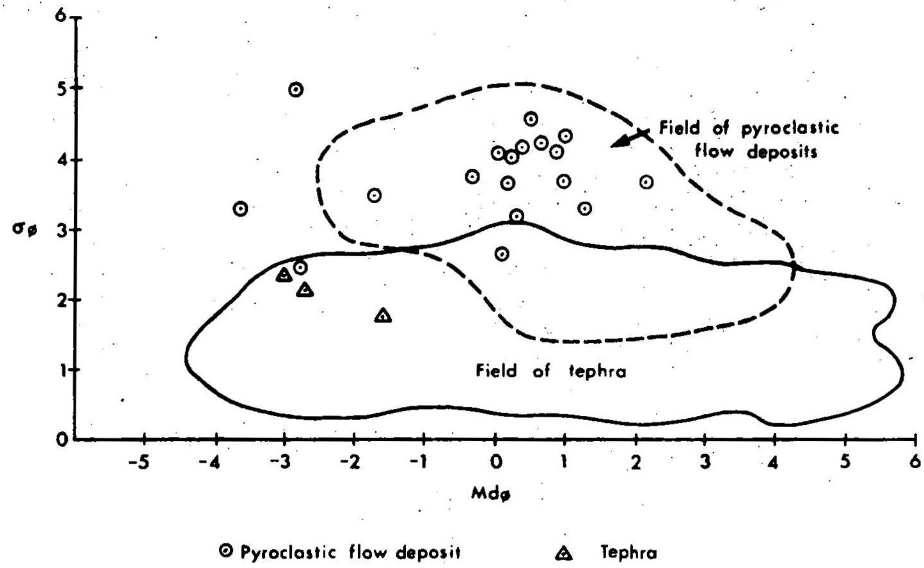

Fig 17. Grain-size characteristics of pumice deposits. Plot of σφ against Mdφ for the samples in Table 7. The fields of pyroclastic flow deposits and tephra are taken from Walker, 1971.

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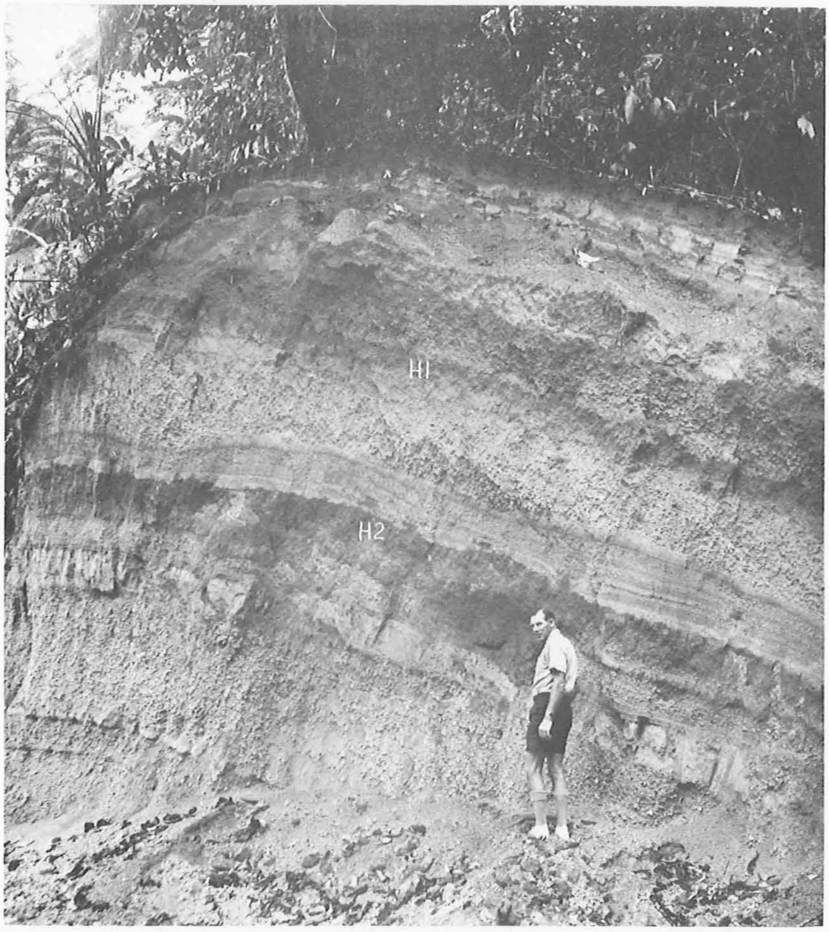


Figure 18. Exposure of pumiceous tephra layers in a road cutting on the caldera rim of Busui volcano. Layers labelled H1 and H2 are buried soil horizons. H2 is overlain by a layer showing shower bedding. Site 70490543. Neg. No. L4141-5 (CSIRO)

Figure 19. Coarse and fine layers of pumiceous tephra; road cutting exposure on the caldera rim of Busui volcano. Site 68490060. Neg. No. L3655-9 (CSIRO).

PAGO VOLCANO

Geology

The only active volcano in the Cape Hoskins area, Pago is a stratovolcano built up mainly of thick dacitic lava flows erupted from a central vent (Figs 5, 6 and 11). It is situated within the caldera of Witori volcano. The summit area of Pago consists of a cinder cone 250 m high, the top of which is 724 m above sea-level. The cone has a roughly circular crater 300 m across, breached to the northeast, inside which is a small subsidiary crater. Several active fumaroles and steam vents occur within the craters and on the sides of the cone.

Eight major lava flows can be identified on the flanks, the largest flow being the youngest. This has a volume of about 0.8 km^3. The flows which are of the aa type, have steep bouldery sides and uneven locally blocky upper surfaces showing transverse arcuate pressure ridges and furrows and in some cases marginal longitudinal lava levees and depressions. These surface features are partly or completely obscured by vegetation on all but the youngest flow, which is the site of numerous active fumaroles and has hot springs issuing from beneath it (Figs 6 and 12).

Pago has been built up since the formation of the caldera of Witori volcano, which was probably formed about 2600 years ago, as described above. It is also younger than the pinnacle inside the caldera, which it partly overlaps. The date of the first Pago eruption is uncertain, but the following evidence indicates that it may have been less than 350 years ago. Charcoal collected from a buried soil horizon near Rikau, on the lower north flank of Witori, has been dated at 320 $\pm$ 170 years B.P. The buried soil is developed on pumice and underlies about 0.5 m of thin-bedded mainly pumiceous tephra that is capped by about 0.15 m of non-pumiceous dacitic tephra and dark top soil. The non-pumiceous tephra probably came from Pago, but the thin-bedded pumiceous tephra is probably derived from volcanic eruptions that took place outside the Cape Hoskins area. In any case it is significant that no pumiceous tephra has been found on any of the Pago lavas, indicating that the lavas are most likely younger than this tephra.

The last eruption of Pago started in 1914 and continued until August 1918, according to the late Father Stamm, who witnessed part of the eruption (personal letter to R.W. Johnson dated 11 August 1969), and Boas, a local chieftain, who described the eruption to the author in 1968. Father Stamm also reported that Pago was active at the turn of the century. During the 1914-18 eruption highly viscous magma was emitted to form the youngest lava flow. The eruption was relatively quiet and was accompanied by only minor explosive activity. However, volcanic ash caused extensive damage to gardens and plantations in the Cape Hoskins area and can be expected to do so again in any future eruptions.

Petrography

Specimens from six of the lava flows on Pago, including the youngest, have been examined petrographically and three have been chemically analysed. The lavas are uniform in composition, and the analyses show that they are low-silica dacites, not basaltic andesites as suggested by Blake & Bleeker (1970). They are made up of phenocrysts up to 1 mm long, of plagioclase, augite, pleochroic orthopyroxene and iron-titanium oxide (Table 6) enclosed in a very fine-grained highly vesicular groundmass. The phenocrysts commonly occur in small glomeroporphyritic groups.

The plagioclase phenocrysts have cores of bytownite (An 70-90) bounded by oscillatory zoned narrow margins of labradorite (An 55 - 70) and in some cases very narrow outer rims of andesine. Small inclusions of volcanic glass and groundmass are commonly present, but are generally restricted to particular compositional zones. Rare phenocrysts or xenocrysts of plagioclase have honeycomb textures, with inclusions of volcanic glass filling small cavities. Augite phenocrysts are equant, pale green in thin section, non pleochroic, and many are twinned. Rarely they have cores of orthopyroxene. Phenocrysts of orthopyroxene are elongate and commonly have thin rims of clinopyroxene. The orthopyroxene is pleochroic from pale pink to pale green. Iron-titanium oxide phenocrysts are equant and smaller than the other phenocrysts.

The groundmass of the lavas consists of flow-aligned crystallites of plagioclase, clinopyroxene, and minor orthopyroxene, together with opaque granules and interstitial colourless silica minerals (either or both tridymite and cristobalite) or isotropic brown glass.

BURU VOLCANO

Geology

Southwest of Witori lies Buru volcano, which consists of a partly preserved volcanic cone about 150 m high and a swampy caldera-like depression to the north. All that is left of the north part of the original cone is a steep-sided semi-circular embayment that probably represents part of a caldera or crater. In contrast the other sides of the cone have relatively gently concave slopes which represent an original constructional volcanic surface. These sides are dissected by gullies radiating outwards from the 'crater'. The caldera-like depression is bounded to the north by an irregular cliff face that cuts into the dissected southwest flank of Witori. This indicates that the depression was probably formed after the caldera eruption of Witori, when pumice deposits blanketed the flanks of that volcano.

The east side of the cone was visited in 1970. It is incised by gullies over 30 m high, on the near vertical sides of which are exposed thick unsorted pyroclastic deposits interpreted as pyroclastic flows. These consist largely of dacitic pumice, but also contain scattered fragments up to 1 m across of porphyritic andesite or dacite and also pitchstone, a chemical analysis of which shows it to be a high-silica dacite containing 69 wt percent silica.

Petrography

The porphyritic andesite or dacite fragments in the pyroclastic flow deposits are comparable petrographically to rocks of similar composition elsewhere in the Cape Hoskins area. They contain abundant small phenocrysts of plagioclase, augite, pleochroic orthopyroxene, and iron-titanium oxides enclosed in a very fine-grained to partly glassy groundmass. The pitchstone contains the same minerals as phenocrysts in a clear non-euxatic colourless glass. The same types of phenocrysts, together with very minor quartz, are present in the pumice that makes up the bulk of the pyroclastic deposits. The fresh pumice glass has a refractive index of 1.522 $\pm$ 0.003, which is higher than that of any of the fresh pumice from Witori volcano, and indicates that the Buru pumice is probably slightly less acid in composition.

TEPHRA

The surfaces of all the volcanoes except Pago, where they are not being actively eroded, are mantled by tephra. At many localities the tephra is several metres thick (Fig. 18). It consists of well defined layers of different colours, textures and compositions, and ranges in grain-size from silt to coarse gravel. The individual layers show undulating bedding, as they mantle the pre-existing topography; some show internal banding termed 'shower-bedding'. Most are made up predominantly of fresh pale grey to white pumice (Fig. 19), but they also contain some lithic fragments, mainly of andesitic and dacitic lava. Scoriaceous lava bombs have also been observed at a few sites. The pumice contains phenocrysts of plagioclase, augite, pleochroic orthopyroxene, iron-titanium oxide, and in some cases either or both quartz and hornblende set in highly vesicular colourless glass that mostly has refractive indices between 1.501 - 1.507. These refractive indices are similar to those of pumiceous glass in the Taupo area New Zealand and indicate probably silica compositions of about 70 wt percent (Ewart, 1963; Huber & Rinehart, 1966).

Buried soil horizons are present at several levels within the tephra deposits. They represent relatively long periods during which no pumiceous tephra was deposited, so that weathering and soil formation were able to take place. In some instances these periods probably lasted several hundreds of years. Buried soils are particularly well displayed in road cuttings on the caldera rim of Busui volcano, west of Oto (Fig. 18). The lowest buried soil here, 7 m below the top of the exposed succession and not visible in Figure 18, contains charcoal dated at 1990 $\pm$ 90 years B.P., indicating that 7 m of tephra has been deposited at this locality within the last 2000 years.

Charcoal dates have also been obtained from the youngest buried soil horizon near Rikau, south of Lolo, and on the track to Lavege east of Witori. The two horizons occur 0.7 m below the surface, and have been dated at 320 ± 170 years and 830 ± 110 years B.P. respectively.

Not all the tephra is pumiceous. For instance, dacitic non-pumiceous tephra was deposited during the last eruption of Pago. However, such tephra is typically much less voluminous than pumiceous tephra and where the land surface is densely vegetated, as on New Britain, it is readily incorporated into the existing topsoil. As a result, non-pumiceous tephra can rarely be identified.

The tephra has been derived from a number of volcanic sources. Some of the pumiceous tephra was no doubt deposited during eruptions of of Buru and Witori volcanoes. Much, however, is probably younger than the last major eruptions of these volcanoes, and must therefore be derived from elsewhere in the New Britain area, such as volcanoes on Willaumez Peninsula and on Lolobau Island. Non-pumiceous tephra from recent eruptions of Ulawun and Langila volcanoes may be present with that from Pago in the thick dark topsoils characteristic of the Cape Hoskins area.

SUMMARY OF VOLCANIC HISTORY OF THE CAPE HOSKINS AREA

As a result of the field work undertaken in 1970 and subsequent K-Ar and C-14 age data, some minor modifications need to be made to the account of the volcanic history given by Blake & Bleeker (1970).

The oldest volcanoes are Ko and Husa in the west and possibly Kapberg in the north, all three of which are in a similar residual stage of erosion. Lavas from Ko have been dated at 0.8 to 0.9 m.y., indicating that this volcano was active during the mid Pleistocene. Busui volcano in the southwest is younger than Husa, which it overlaps, but is older than Oto. It is probably formed of pumiceous pyroclastics deposited during a series of explosive eruptions, and its activity may have culminated in a paroxysmal caldera-forming eruption. Oto volcano was active about 190 000 years ago and is therefore of late Pleistocene age. Mululus is somewhat younger, as lavas from it have been dated at 111 000 to 63 000 years. Mataleloch overlaps onto Mululus and hence is younger still. It is more eroded and therefore probably older than Lolo to the northeast, which is the only extinct volcano with a well preserved summit crater. Eruptions of Oto, Mululus, Mataleloch and Lolo were probably of the Vesuvian type, with explosive activity accompanying the extrusion of lava flows.

Of the three remaining volcanoes in the area Witori is considered to be the oldest. It had a paroxysmal eruption about 2600 years ago, when the caldera is thought to have formed. During this eruption large volumes of pumice were emitted both as pyroclastic flows confined to the flanks of Witori and as tephra which blanketed most of the surrounding area. A similar eruption of Buru volcano probably took place shortly after. As a result of this eruption the northern part of the cone of Buru disappeared and a caldera-like depression was formed to the north. Pago, the youngest volcano and the only one considered potentially active, has been built up inside the caldera of Witori volcano by a series of eruptions during which thick viscous lava flows were emitted, accompanied by relatively minor explosive activity. The first eruption of Pago may have occurred less than 350 years ago and the last took place in 1914-18, when the youngest lava flow appeared and explosive activity was sufficient to produce ash showers that caused serious damage to the vegetation in the Cape Hoskins area.

Present day volcanic activity is confined to solfataras and fumaroles on Pago and three thermal areas on the southeast lower flank of Witori.

TABLE 3. STATISTICS OF VOLCANOES OF THE CAPE HOSKINS AREA

Name	Height a.s.l. (m)	Height of edifice (m)	Form	Composition of Products	Age
Pago	724	700	High angle cone	Low-silica dacite	Holocene, last eruption 1914-18
Witori	700	700	Low angle cone with central caldera	Low-silica andesite to rhyolite	Holocene, last major eruption 2600 years B.P.
Buru	300	250	Breached cone and caldera	Dacite and probably andesite	Holocene, last major eruption about 2500 years B.P.
Lolo	818	810	High angle cone	Low and high silica andesite	Late Pleistocene
Mataleloch	672	670	High angle cone	Low and high silica andesite	Late Pleistocene
Mululus	1054	1050	High angle cone	Low-silica andesite to high-silica dacite	Late Pleistocene 60 000-110 000 years B.P.
Oto	1305	1250	High angle cone	Basalt to high-silica dacite	Late Pleistocene about 190 000 years B.P.
Busui	370	360	Low angle cone with caldera	Probably andesite to rhyolite	Late Pleistocene, older than Oto and younger than Husa
Ko	600	550	Eroded cone, no constructional surface preserved	Low-silica andesite	Mid Pleistocene, 750 000-950 000 years B.P.
Husa	550	500	Eroded cone, no constructional surface preserved	Probably low-silica andesite	Mid Pleistocene
Kapberg	384	380	Eroded cone, no constructional surface preserved	Low-silica andesite	Probably mid Pleistocene

TABLE 4. POTASSIUM-ARGON AGES ON WHOLE ROCK LAVAS FROM THE CAPE HOSKINS AREA, NEW BRITAIN

Determined by Dr I. McDougall, Australian National University, Canberra

BMR Sample No.	ANU Sample No.	K (wt. %)		Rad. Ar^{40} ($\times 10^{-13}$ md/g)	$\frac{\text{Atm. } Ar^{40}}{\text{Total } Ar^{40}} \times 100$	Calculated Age (m.y.)	Locality
68490084	70-465	1.194) 1.200)	1.197	2.363 2.033	96.9 97.3	0.111 ± 0.008 0.095 ± 0.012	Mululus Volcano, north flank, 120 m a.s.l. Lava flow exposed on W bank of creek
68490092A	70-466	0.621) 0.622)	0.621	0.929 0.703	96.9 97.5	0.084 ± 0.006 0.063 ± 0.014	Mululus Volcano, west flank, 335 m a.s.l. Lava flow forming upper part of waterfall
68490162	70-467	0.739) 0.741)	0.740	0.896	93.9	0.068 ± 0.004	Mululus Volcano, southeast flank, 270 m a.s.l. Basal part thick lava flow forming waterfall
68490151	70-463	0.208) 0.214)	0.211	0.734	98.7	0.195 ± 0.029	Oto Volcano, northeast flank, 245 m a.s.l. Lava flow exposed on west bank of creek
68490152C	70-464	0.462) 0.463)	0.462	-	100	<0.19	Oto Volcano, northeast flank, 315 m a.s.l. Lava flow exposed on east bank of creek
68490171A	70-155	0.411) 0.412)	0.411	6.809	90.9	0.931 ± 0.031	Ko Volcano, south flank, 76 m a.s.l. Lava flow exposed in Ko Creek
68490172	70-156	0.730) 0.731)	0.730	10.20	62.6	0.785 ± 0.011	Ko Volcano, south flank, 90 m a.s.l. Lava flow exposed on sides of Ko Creek
68490176	70-157	0.798) 0.799)	0.799	11.24	71.2	0.792 ± 0.015	Ko Volcano, south flank, 135 m a.s.l. Lava flow exposed in southerly flowing tributary of Ko Creek

TABLE 5. C-14 AGES OF CHARCOAL FROM BURIED SOIL HORIZONS IN THE CAPE HOSKINS AREA, NEW BRITAIN

Determined by Dr K. Kigoshi, Gakushuin University, Tokyo

Sample No.	Age B.P. (years before 1950)	Sample Site
GaK-2163	1190 ± 90	0.55 - 0.73 m below top of alluvial terrace, site 68490125, lower northwest flank of WITORI
GaK-2164	1740 ± 100	2.00 - 2.13 m below top of alluvial terrace, site 68490125, lower northwest flank of WITORI
GaK-2167	2590 ± 300	3 m below top of cliff, underlying layer 2 m thick of coarse tephra, site 68490138, coast near Galilo, lower northeast flank of WITORI
GaK-3071	830 ± 110	0.65 - 0.7 m below surface, highest buried soil horizon in soil pit on Lavege track, site 70490593, lower east flank of WITORI
GaK-3072	1990 ± 90	7 m below top of road cutting, site 70490504, rim of BUSUI caldera southwest of OTO
GaK-3074	9460 ± 150	5 m below top of cliff, underlying water-laid pumiceous sands and gravels, site 70490594, coast north of LOLO
GaK-3076	2590 ± 250	Underlying pumice, including moderately welded pyroclastic flow, site 70490545, lower southwest flank of WITORI
GaK-3077	1530 ± 100	Underlying thick coarse tephra and overlying unwelded pyroclastic clastic flow deposits, site 70490528, gully head near caldera rim, upper northeast flank WITORI
GaK-3079	320 ± 170	0.65 - 0.7 m below surface, highest buried soil horizon in soil pit near Rikau, site 70490595, lower north flank WITORI

TABLE 6. MODAL ANALYSES OF 27 ROCKS FROM THE CAPE HOSKINS AREA

Volcano	Sample Number	Volume % phenocrysts: Plagioclase	Olivine	Ortho-Pyroxene	Augite	Fe-Ti Oxides	Quartz	Total % phenocrysts	Rock type	Locality
Ko	68490171B	6	-	1	1	-	-	8	Low-silica andesite	Lava flow, S. flank, 75 m a.s.l.
	68490174	23	-	3	4	1	-	32	Low-silica andesite	Lava flow, S. flank, 115 m a.s.l.
Kapberg	68490047	27	-	4	2	1	-	34	Low-silica andesite	Lava flow, NE flank, 130 m a.s.l.
Oto	68490147B	16	-	1	1	1	-	16	High-silica dacite	Boulder in stream, N flank, 320 m a.s.l.
	68490151	26	1	5	2	-	-	33	Basalt	Lava flow, NE flank, 245 m a.s.l.
	68490152B	26	1	3	3	1	-	32	Low-silica andesite	Lava flow, NE flank, 315 m a.s.l.
	68490153	18	-	1	2	1	-	22	Low-silica dacite[1]	Cumulodome, NE flank, 390 m a.s.l.
	68490154	19	-	2	4	1	-	26	Low-silica dacite	Youngest lava flow, NE flank, 430 m a.s.l.
Mululus	68490092B	21	-	1	2	1	-	25	Low-silica dacite[2]	Boulder in stream, NW flank, 305 m a.s.l.
	68490134C	18	-	1	3	1	-	23	Low-silica andesite	Boulder in stream, W flank, 70 m a.s.l.
	68490159A	21	1	1	5	1	2	31	Low-silica dacite[1]	Boulder in stream, E flank, 125 m a.s.l.
	68490162	10	1	1	2	1	1	15	High-silica andesite	Cumulodome, E flank, 270 m a.s.l.
	68490164	24	-	1	3	1	1	30	High-silica dacite	Cumulodome, E flank, 240 m a.s.l.
Mataleloch	68490077	29	1	5	4	1	-	38	Low-silica andesite	Boulder in stream, E flank, 90 m a.s.l.
Lolo	68490003	26	1	5	3	-	-	34	Low-silica andesite	Boulder on steep ridge crest, SW flank 435 m a.s.l.
	68490013	22	-	1	1	1	-	24	Low-silica andesite	Lava flow, SW flank, 170 m a.s.l.
	68490102	23	-	3	2	-	-	28	Low-silica andesite	Lava flow, E flank, 170 m a.s.l.
	68490108	18	1	2	2	1	-	23	High-silica andesite	Lava flow, NW flank, 70 m a.s.l.
Witori	68490025	20	-	1	3	1	-	23	Low-silica andesite	Lava flow, base of caldera wall N of Pago, 200 m a.s.l.
	68490036F	3	-	1	1	1	-	3	Rhyolite	Boulder in stream, N flank, 300 m a.s.l.
	70490548A	3	-	1	1	1	-	5	High-silica andesite[3]	Boulder in agglomerate at base of caldera wall SE of Pago, 60 m a.s.l.
	70490579B	6	-	1	1	1	-	8	High-silica andesite[4]	Lava flow, caldera wall N of Pago, 330 m a.s.l.
	68490030	7	-	1	1	1	-	8	High-silica dacite	Lava forming NW side of pinnacle inside caldera
Pago	68490031	6	-	1	1	1	-	8	Low-silica dacite	1914-18 lava flow, E of cone
	68490033	6	-	1	1	1	-	8	Low-silica dacite	Lava flow, NE of cone, 380 m a.s.l.
	70490557	8	-	1	1	1	-	10	Low-silica dacite	Lava flow, S of cone, 45 m a.s.l.
Buru	70490557	13	-	1	1	1	-	16	High-silica dacite	Boulder in pyroclastic flow deposit, NE flank of cone, 130 m a.s.l.

Notes: 1 - contains 5% vesicles 2 - contains 1% xenoliths 3 - contains 18% vesicles 4 - contains 17% vesicles

TABLE 7. GRAINSIZE CHARACTERISTICS OF PUMICE DEPOSITS

A. PYROCLASTIC FLOW DEPOSITS

Specimen No.	Md(mm)	Mdø	ø	Locality
70490514	0.2	2.2	3.7	Flow unit 1 m above base of composite flow deposit 8 m thick; upper northeast flank WITORI, 160 m a.s.l.
70490524	0.4	1.0	3.7	Flow unit 5 m above base of composite flow deposit 10 m thick; upper northeast flank WITORI, 120 m a.s.l.
70490528A	6.7	-2.8	5.0	Flow unit 3 m below top of composite flow deposit; caldera rim northeast side WITORI, 365 m a.s.l.
70490528D	0.2	2.2	3.7	Flow unit 1 m above 70490528A.
70490531	0.9	0.1	2.7	2 m above base of flow deposit 15 m thick; upper northwest flank WITORI, 290 m a.s.l.
70490533B	6.7	-2.8	2.55	Flow unit 3 m above basal exposure of composite flow deposit over 60 m thick; caldera rim northwest side WITORI, 475 m a.s.l.
70490533C	0.5	0.9	4.2	Flow unit 1 m below 70490533B.
70490541	1.2	0.3	3.2	Flow deposit 30 m above creek bed; lower southwest flank WITORI, 120 m a.s.l.
70490546E	0.9	0.2	3.7	Lower unit of composite flow deposit 6 m thick; upper southwest flank WITORI, 80 m a.s.l.
70490546G	0.4	1.3	3.3	Upper unit of same flow deposit as 70490546E.
70490556	0.8	0.4	4.1	Massive flow deposit forming hill 15 m high; southeast caldera floor WITORI, 110 m a.s.l.
70490558	1.2	-0.3	3.8	Unit of composite flow deposit 30 m thick; gully on east flank of cone, BURU, 130 m a.s.l.
70490562	8.0	-3.0	2.4	Water-sorted part of flow deposit forming hill 7 m high; south caldera floor, WITORI, 75 m a.s.l.
70490567A	3.3	-1.7	3.5	Flow deposit 4 m thick; southeast caldera wall WITORI, 65 m a.s.l.
70490571	0.7	0.6	4.2	Flow deposit at base of cliff; upper southeast flank WITORI, 35 m a.s.l.
70490573	1.0	0.1	4.1	Flow deposit forming hill 10 m high; caldera flow WITORI east-southeast of Pago, 60 m a.s.l.

TABLE 7 contd.

Specimen No.	Md(mm)	Mdϕ	ϕ	Locality
70490585	11.9	-3.6	3.3	Flow deposit forming ridge 15 m high; caldera floor WITORI west of PAGO, 270 m a.s.l.
70490588	0.9	0.2	4.1	Flow deposit forming ridge 12 m high; caldera floor WITORI west-northwest PAGO, 205 m a.s.l.
70490592A	0.7	0.5	4.6	Base of non-welded zone overlying moderately welded flow deposit, lower northwest flank WITORI near Waisissi, 85 m a.s.l.
70490592B	0.5	1.0	4.3	Flow deposit 13 m above 70490592A.
				B. AIRFALL DEPOSITS
70490545B	8.0	-3.0	2.4	Layer 2 m below top of buried soil underlying partly welded flow deposit; lower southwest flank WITORI, 100 m a.s.l.
70490546A	3.0	-1.57	1.8	Layer 3 m thick capping pyroclastic deposits; upper southwest flank WITORI, 100 m a.s.l.
70490569A	6.7	-2.7	2.15	Layer 15 cm thick underlying pyroclastic deposits 15 m thick; upper southeast flank WITORI, 65 m a.s.l.

PART 3: WULAI AND KIMBE ISLANDS, DUFAURE AND WAGO VOLCANOES, AND VOLCANOES OF SOUTHERN WILLAUMEZ PENINSULA

INTRODUCTION

Most of the volcanoes described in this section form an irregular chain that makes up the southern half of Willaumez Peninsula and a restricted area at the base of the peninsula (Fig. 1). Exceptions are Wulai and Kimbe, minor volcanic centres that form small islands in Kimbe Bay: they were examined by Macnab, Ryburn and Johnson, with the part-time assistance of P. Pieters, at various times between 10 and 27 October, 1969.

The geology and petrology of the northern half of Willaumez Peninsula, including the area around Talasea (Fig. 1), has been described by Lowder & Carmichael (1970) and Lowder (1970), and by others. Consequently only a few localities in this part of the peninsula were visited by the 1969 BMR field party. Some aspects of the overall geology of the peninsula are discussed at the end of this part.

WULAI ISLAND

Geology

The small volcanic islands of Wulai and Kimbe in Kimbe Bay are isolated both from each other and from the main groups of volcanoes in the Cape Hoskins area and on Willaumez Peninsula (Fig. 1).

Wulai, the larger of the two islands, is about 9 km north of the New Britain coastline, and about 19 km southeast of Kimbe Island. It consists of two roughly triangular parts joined by a narrow north-south isthmus, and has a prominent bay on its eastern side (Fig. 20). The island rises no more than a few tens of metres above sea-level. It is uninhabited, but is visited by mainland villagers who grow coconuts there. Thick vegetation covers most of the island, and rocks are well exposed only along the shoreline. The entire island is fringed by coral reefs which join up northwards with an enclosing barrier reef through which there are three entrances.

No constructional volcanic forms have been identified on Wulai, and the island is presumed to be a deeply eroded volcanic centre. Lava flows and volcanic rudites are exposed along the shoreline. A strong fissility is developed in the lava flows of some outcrops, and in others the lava is well-jointed.

Petrology

Twenty-six samples were collected from Wulai Island by Macnab and Johnson. Petrographic examination of these samples, and four chemical analyses showing silica contents ranging between 52.2

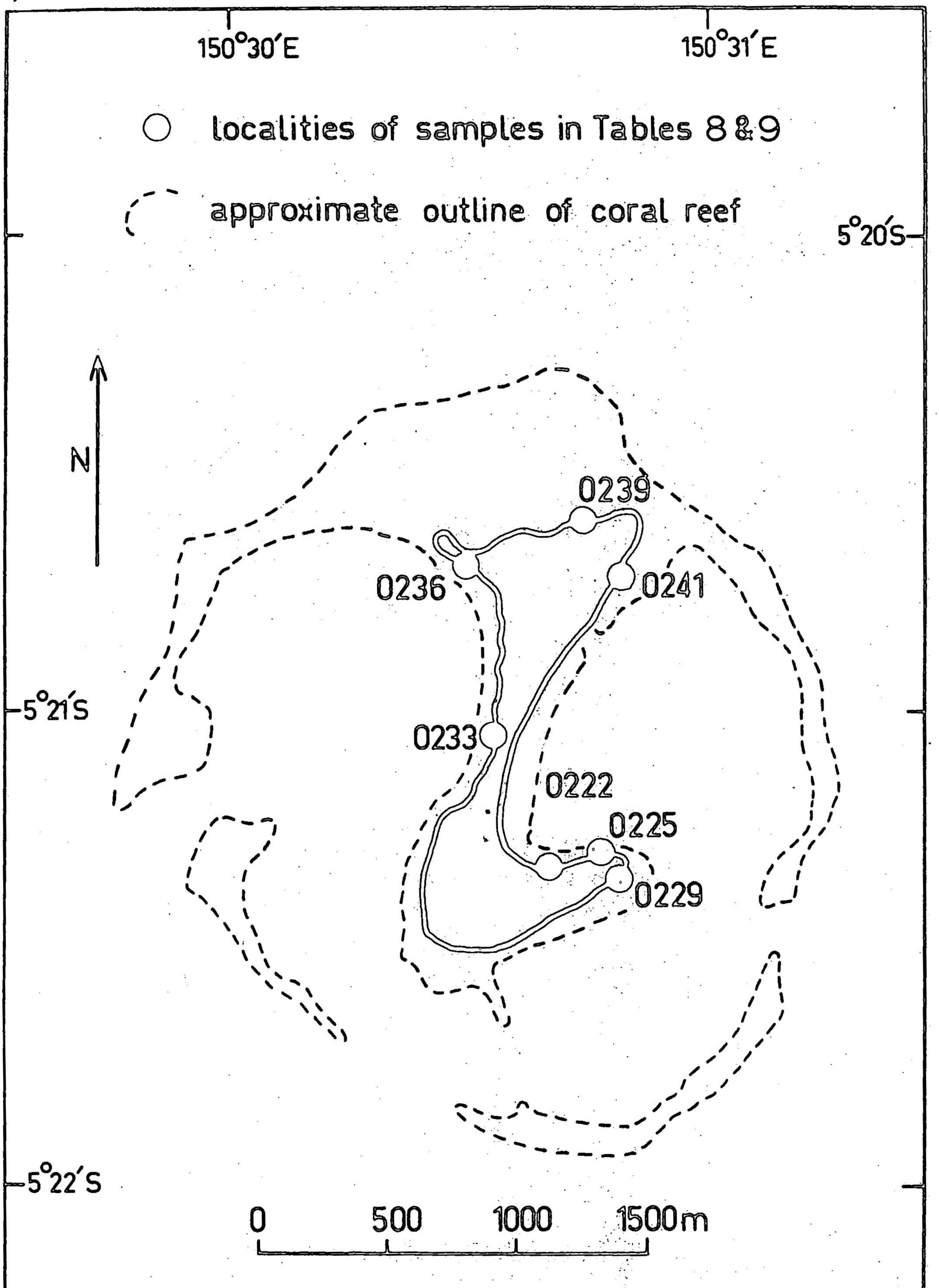


Fig 20. Sketch map of Wulai Island, adapted from German Admiralty Chart (1915)

To accompany Record 1972/133

and 56.7 wt percent, indicate that the rocks are basalts and low-silica andesites. Table 8 gives seven modal analyses of samples whose localities are listed in Table 9.

Wulai rocks are highly porphyritic, the most abundant type of phenocryst being zoned plagioclase. Pleochroic orthopyroxene is the second most common phenocryst mineral, but is not present in samples rich in olivine. In the other rocks it is more abundant than augite and commonly occurs in clusters. Augite phenocrysts are most abundant in olivine-rich rocks, and are generally poorly developed, or absent, in rocks containing orthopyroxene phenocrysts. Iron-titanium oxide phenocrysts are absent in samples rich in olivine.

Olivine phenocrysts are present in many samples, but mostly in amounts less than 1 percent. Many are partly or completely altered to deep rust-red 'iron oxide'. In a few rocks altered olivine grains have narrow overgrowths of colourless olivine, indicating that some olivine crystallised after the alteration, which must have taken place at a high temperature. Coronas of fine-grained pleochroic orthopyroxene are present on the olivine phenocrysts of many rocks, and in some cases the coronas also contain iron-titanium oxide grains. In a few samples, olivine and pleochroic orthopyroxene form aggregates, and sample 0229A contains olivine phenocrysts intergrown with, as well as rimmed by, orthopyroxene.

The groundmass of most rocks is fine-grained, and is composed mainly of plagioclase, augite, orthopyroxene, iron-titanium oxides, low-2V clinopyroxene, and high-temperature silica polymorphs.

TABLE 8 . MODAL ANALYSES OF 7 ROCKS FROM WULAI ISLAND

Sample number (prefix 51NG)	Volume % phenocrysts					Total % phenocrysts
	Plagio-clase	Olivine	Ortho-pyroxene	Augite	Fe-Ti oxides	
0222A	38	-	5	1	<1(a)	44
0225	36	-	4	2	1	43
0229B	34	<1	1	-	<1(a)	35
0233	27	1	2	1	<1	31
0236	24	<1(b)	10	5	<1	39
0239	28	4	-	3	-	35
0241	30	4	-	5	-	39

(a) rare microphenocrysts

(b) hole in slide rimmed by orthopyroxene and iron-titanium oxides.

TABLE 9 . LOCALITY INDEX FOR SAMPLES OF TABLE 8 , AND FOR THOSE REFERRED TO IN TEXT

Sample	Locality description
0222A	clast in volcanic rudite, southern end of bay on eastern side.
0225	*in situ* lava flow, southern end of bay on eastern side.
0229A, 0229B	*in situ* lava outcrops on southeastern corner of island.
0233	*in situ* lava showing strong fissility, west coast.
0236	*in situ* lava, near northwestern tip of island.
0239	*in situ* lava flow, headland on north coast.
0241	boulder on headland, northeastern coast.

KIMBE ISLAND

Geology

Kimbe Island is about 33 km east of Willaumez Peninsula, and 25 km north-northwest of the Cape Hoskins area (Fig. 1). No large-scale maps or aerial photographs are available of the island, which is more or less circular, a few hundred metres in diameter, and about 40-50 m high. It is thickly vegetated and uninhabited, and has no fringing coral reefs. The island has a comparatively flat top, and its sides rise steeply from the shoreline, having maximum slopes between 40° and 50°. Macnab and Johnson visited Kimbe Island on 11 October 1970.

Rock exposures are restricted to the coast, where lava crops out in many places. Deposits consisting of lava boulders are also present, and oxidized scoriae is exposed at one locality in the southeast. Some lava is massive, some is slightly scoriaceous, and some shows flow-banding. Some also contains coarse-grained plutonic inclusions up to a few centimetres in diameter.

Petrology

Nineteen rocks from Kimbe Island have been examined in thin section. Most contain olivine phenocrysts, and chemical analyses of four such samples, which show silica values ranging between 49.2 and 52.6 wt percent, indicate that the most common rock type is basalt. A few samples contain no olivine, and these are probably andesites. Modal analyses of seven rocks are given in Table 10, and the localities of the samples are listed in Table 11.

Most rocks contain more than 30 percent total phenocrysts. A few olivine-free rocks, such as samples 0243B and 0245A have less than 20 percent phenocrysts, and one sample, 0246, is almost aphyric. Plagioclase is the dominant phenocryst mineral, and none of the rocks in Table 10 contains more than a few percent of any one type of ferro-magnesian phenocryst. In most rocks, phenocrysts of augite predominate over those of orthopyroxene. Iron-titanium oxide phenocrysts are absent or sparse. Microphenocrysts of apatite are present in a few samples.

Olivine phenocrysts are present in most samples, but not in amounts greater than 3 percent. In some rocks, the olivine phenocrysts are unaltered, but in many they are partly or wholly pseudomorphed by 'iddingsite'. They commonly have narrow rims of iron-titanium oxides, and in a few samples are surrounded by a poorly-defined, fine-grained, oxide-free zone that appears to be made up principally of pyroxene. In a few cases coronas of orthopyroxene or augite are present.

The groundmass minerals are plagioclase,iron-titanium oxides, augite, pleochroic orthopyroxene, and low-2V clinopyroxene. Olivine is also present in the groundmass of the sparsely porphyritic basalt, 0246, and high-temperature silica polymorphs are present in some vesicles. The groundmass of the olivine free samples (0243, 0245) is heterogeneous, consisting of colourless glassy areas, crowded with microlites that appear to be mainly plagioclase, enclosed in a dark brown, microlite-rich glass. Similar textures have been observed in high-silica andesites and dacites from other Late Cainozoic volcanoes in New Britain, such as those from Lolobau Island and the Lake Hargy area (Johnson, 1970c, 1971).

TABLE 10. MODAL ANALYSES OF 7 ROCKS FROM KIMBE ISLAND

Sample number (prefix 51NG)	Volume % phenocrysts					Total % phenocrysts
	Plagio-clase	Olivine	Ortho-pyroxene	Augite	Fe-Ti oxides	
0242	29	1	2	2	<1	34
0243B	14	< 1(a)	1	1	1	17
0245A(b)	14	-	< 1	1	< 1	15
0245B	34	2	<1	4	-	40
0246	< 1	<1	<1	<1	<1	ca 1
0248	29	3	<1	6	<1	38
0250A	35	1	2	4	<1	42

(a) patches of secondary minerals which may be pseudomorphs of olivine.

(b) also contains a few microphenocrysts of apatite

TABLE 11. LOCALITY INDEX FOR SAMPLES OF TABLE 10

Sample	Locality
0242	loose boulder, southeastern coast
0243B	*in situ* lava, south coast
0245A }	loose boulders, southwestern coast
0245B }	
0246	loose boulder, west coast
0248	loose boulder, northwestern coast
0250A	loose boulder, northeastern coast

DUFAURE AND WAGO VOLCANOES

Geology

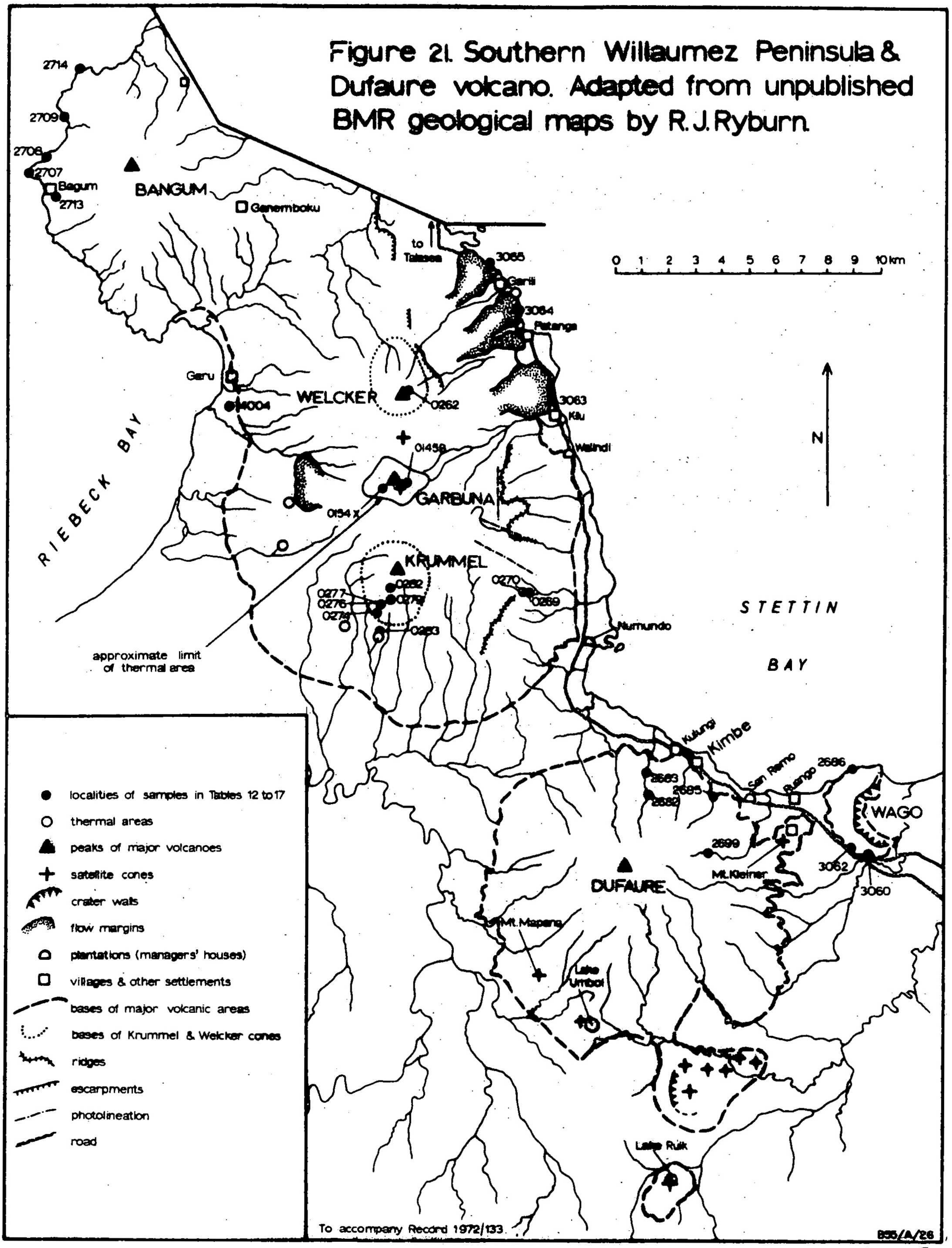
Dufaure is a dissected, central volcano on the southwestern side of Stettin Bay, southeast of the southern end of Willaumez Peninsular (Figs 1 and 21).

The base of Dufaure is roughly circular, and has a diameter of about 11 km (Fig. 21). According to the Lae Sheet, the volcano rises to 752 m above sea-level. The average slope of the outer flanks is about 4°. In profile, Dufaure has subdued relief compared to the nearby steep-sided volcanoes of the Cape Hoskins area and southern Willaumez Peninsula. There are no remnants of a summit crater, and no planezes are preserved. This indicates that Dufaure has been dissected to a 'residual mountain' stage of erosion (Kear, 1957), and much of its activity may have taken place before many of the volcanoes on Willaumez Peninsula were built. However, numerous satellite cones are scattered around the periphery of Dufaure, particularly in the south, and indicate more recent activity. Mount Wago, the largest of these satellite cones, is on the northeastern edge of Dufaure.

An unsealed road from Talasea to Cape Hoskins follows the northern margin of Dufaure and cuts across the southern flank of Wago; it passes through Kimbe, the site of the new District Headquarters, and through San Remo Plantation (Fig. 21). Apart from these settlements and a few villages close to the road, the Dufaure area is uninhabited, and is covered entirely by rainforest.

Wago is a crescentic remnant of a volcanic cone which originally had a basal diameter of about 3.5 km. The crescent is concave to the east, and the highest point on the rim is about 200 m above sea-level.

Figure 21. Southern Willaumez Peninsula & Dufaure volcano. Adapted from unpublished BMR geological maps by R.J.Ryburn.



A steep crater wall is preserved on the concave side, and the convex outer slopes are deeply dissected. Exposures are present along the coast and in a road-cut to the south.

The most extensive area of satellitic volcanic activity is on the south side of Dufaure. In the extreme south, Lake Ruik occupies a crater, about 500 m in diameter, in an elongate hill that was probably an outlying minor centre of activity. North of Lake Ruik a cluster of hills and craters form a volcanic area connected to the southern margin of Dufaure volcano. Five of these hills are minor cones with craters aligned east-west, but others, to the southwest, appear to be parts of the dissected walls of a crater within which there is another satellite cone. Lake Umbol is a second crater lake on the southern periphery of Dufaure. Mount Mapana, about 3 km to the northwest, appears to be a minor cone and Mount Kleiner, on the northeastern flank of Dufaure immediately southwest of Wago, is probably another site of satellitic activity.

Ryburn and Macnab visited Wago and exposures on the northern flank of Dufaure at various times between 13 and 15 October 1970. The exposures observed on Dufaure were of lava flows and volcanic rudites; many of these rocks appeared to be weathered, and samples suitable for chemical analysis were selected mainly from boulders in streams. Some of the samples are light-coloured and contain amphibole, suggesting high-silica andesite and dacite compositions. Lava flows also crop out at the coast on the north side of Wago and in the road cutting in the south, these flows appear to be more basic than those from Dufaure, and contain no amphibole.

Petrology

Dufaure. Thin section examination of seventeen rocks and chemical analyses of five samples show that Dufaure is made up of andesite and dacite. The silica range of the five analysed samples is 57.6 to 63.4 percent. Modal analyses of eight rocks are shown in Table 12 and the localities of these samples are given in Table 13.

The Dufaure rocks are highly porphyritic, some comprising nearly 50 percent phenocrysts (Table 12). Plagioclase phenocrysts are the most abundant, forming 18 - 34 percent of the analysed rocks. A few percent of pleochroic orthopyroxene phenocrysts are present in all the rocks, and augite phenocrysts form over 10 percent in some samples but are absent or rare in samples containing amphibole. Some augite phenocrysts have cores of orthopyroxene, and some orthopyroxene phenocrysts are rimmed by augite. Most samples contain between 1 and 2 percent iron-titanium oxide phenocrysts.

Two samples contain 8 percent amphibole phenocrysts and up to 3 percent quartz phenocrysts (2683A, C, Table 12). In both samples the amphibole is hornblende with the following pleochroic scheme: $\gamma = \beta$ dark reddish brown $> \alpha$ pale yellowish brown, and is partly pseudomorphed by iron-titanium oxides and pyroxene.

Olivine phenocrysts are rare, and those present are either pseudomorphed by fine-grained aggregates which are probably 'iddingsite', or are rimmed or pseudomorphed by iron-titanium oxides and pleochroic orthopyroxene. Olivine phenocrysts are not present in samples containing less than 5 percent augite phenocrysts.

The groundmass minerals most easily recognized are plagioclase, iron-titanium oxides, and less common augite and pleochroic orthopyroxene.

Most samples also contain colourless minerals that have a low birefringence, low refractive indices, and no twinning; these are probably high-temperature silica polymorphs and possibly also alkali feldspar. Amygdaloidal tridymite is present in a few samples. The groundmass of the amphibole-bearing samples is spherulitic pitchstone.

Wago. Most of the seven rocks from Wago cone that have been examined are more basic than those from Dufaure volcano. Most contain olivine phenocrysts, and are probably basalt or low-silica andesite. Modal analyses of three rocks from Wago are given in Table 12, and their localities are listed in Table 13.

The rocks examined all contain phenocrysts of plagioclase, augite, and pleochroic orthopyroxene, and in most olivine and iron-titanium oxide phenocrysts are also present. No amphibole phenocrysts are present. In some samples, olivine phenocrysts are pseudomorphed by brown, fine-grained aggregates which are probably 'iddingsite'. In two samples, one of which is 3062A, olivine phenocrysts are rimmed by orthopyroxene grains.

The phenocrysts are set in a fine-grained groundmass consisting of plagioclase, iron-titanium oxides, augite, orthopyroxene, interstitial cristobalite, and amygdaloidal cristobalite and tridymite.

TABLE 12. MODAL ANALYSES OF 11 ROCKS

FROM DUFAURE AND WAGO VOLCANOES

Group	Sample number (prefix 51NG)	Volume % phenocrysts							Total % pheno-crysts
		Plagio-clase	Oliv-ine	Ortho-pyroxene	Augite	Fe-Ti Oxides	Quartz	Amphi-bole	
1.	2682	26	-	2	2	<1	-	-	30
	2683A	34	-	2	<1	1	3	8	48
	2683C	33	-	3	-	2	2	8	48
	2683D	18	-	2	1	<1	-	-	21
	2683E	24	<1(a)	4	5	1	-	-	34
	2685A	23	<1(a)	2	10	1	-	-	36
	2685B	23	-	3	11	1	-	-	38
	2699	22	<1(a)	3	13	1	-	-	39
2.	2686	14	<1	<1	<1	-	-	-	14
	3060	17	3(a)	3	6	<1	-	-	29
	3062A	20	1	2	6	-	-	-	29

(a) mainly pseudomorphed by orthopyroxene and iron-titanium oxides, or by "iddingsite"

TABLE 13. LOCALITY INDEX FOR SAMPLES OF TABLE 12

Group	Sample	Locality
1. Dufaure Volcano	2682	*in situ* lava flow, stream on northern flank
	2683A, 2683C, 2683D, 2683E	boulders in stream on northern flank
	2685A, 2685B	boulders in stream on northeastern flank, southeast of Kimbe
	2699	boulder in stream on eastern flank
2. Wago cone	2686	boulder on point, north coast
	3060	*in situ* lava flow, road-cut in southern flank
	3062A	boulder on southern slope

KRUMMEL, GARBUNA, AND WELCKER VOLCANOES

Geology

Krummel, Garbuna, and Welcker are three volcanic peaks (Fisher, 1957) aligned from south to north along the crest of an elliptical, shield-like, volcanic foundation on the southern part of Willaumez Peninsula (Fig. 21). The base of the elliptical shield is roughly 19 km by about 13 km, and its long axis is oriented about north-northwest.

Krummel and Welcker are small cones with bases no greater than about 3 km in diameter. The sides of the two cones have maximum slopes of about 30°, in contrast with the slope of the shield, which is generally less than 10°. Garbuna volcano lies on an irregular ridge joining Krummel to Welcker. It has a poorly defined conical form, probably due mainly to alteration and destruction of its central summit area by thermal activity. The presence of several minor eruptive centres between Krummel and Welcker is also suspected but these have not been confirmed because of the poor quality of the available aerial photographs. No satellite cones appear to be present either on the outer flanks of the volcanoes or on the shield foundation.

The three volcanoes are incised by streams in deep V-shaped gorges which radiate outwards from the summit areas. Planezes are preserved on the lower slopes of the cones. The streams have also cut into the low-angle shield, but less deeply than on the high-angle cones.

Lavas samples from Krummel are low-silica andesites, whereas those from Garbuna and Welcker are high-silica andesites and dacites.

<u>Krummel</u> (also known as Worri) volcano rises to 896 m above sea-level (Lae Sheet), and has a summit crater, a few hundred metres in diameter, which is breached to the northwest. The volcano is covered by rainforest, and exposures are mainly confined to stream sections. On 27 October 1969, Johnson ascended the southern flank of Krummel, and

observed outcrops mainly of lava flows but also of clastic rocks, showing that Krummel, like most steep-sided volcanoes in New Britain, is a stratovolcano.

The summit region of <u>Garbuna</u> volcano has extensive vegetation-free areas due to thermal activity (Fig. 22). These cover about 4 km^2, and probably form the most extensive area of present-day thermal activity in Papua New Guinea. Fumaroles, solfataras, bubbling mud springs, and hot patches of earth are all abundant throughout this summit region, and they have deposited sublimate minerals, including sulphur.

Fisher visited Garbuna in 1938 (Fisher, 1939; Fisher & Noakes, 1942) and described (Fisher, 1957) the central part of the Garbuna thermal area as:

> '... a moderately well defined crater about 200 m in diameter, breached towards the SW. The crater floor is occupied at the northern end by an almost flat-lying deposit of soft mudstone, probably laid down originally in a small crater lake. These beds are now being eroded.
>
> Over an area 410 m long from north to south by 200 m across, partly within the crater which is at the north end of this area, and partly on the gentle southern slope, fumaroles (solfataras) are sporadically distributed, together with hot springs, mud springs and quietly steaming areas of sulphur. Gases issue from some of the fumaroles under considerable pressure and around many of them domes of crystalline sulphur 2 - 3 m in height have been built up. H_2S, SO_2, CO_2, HCl were all observed to be present.'

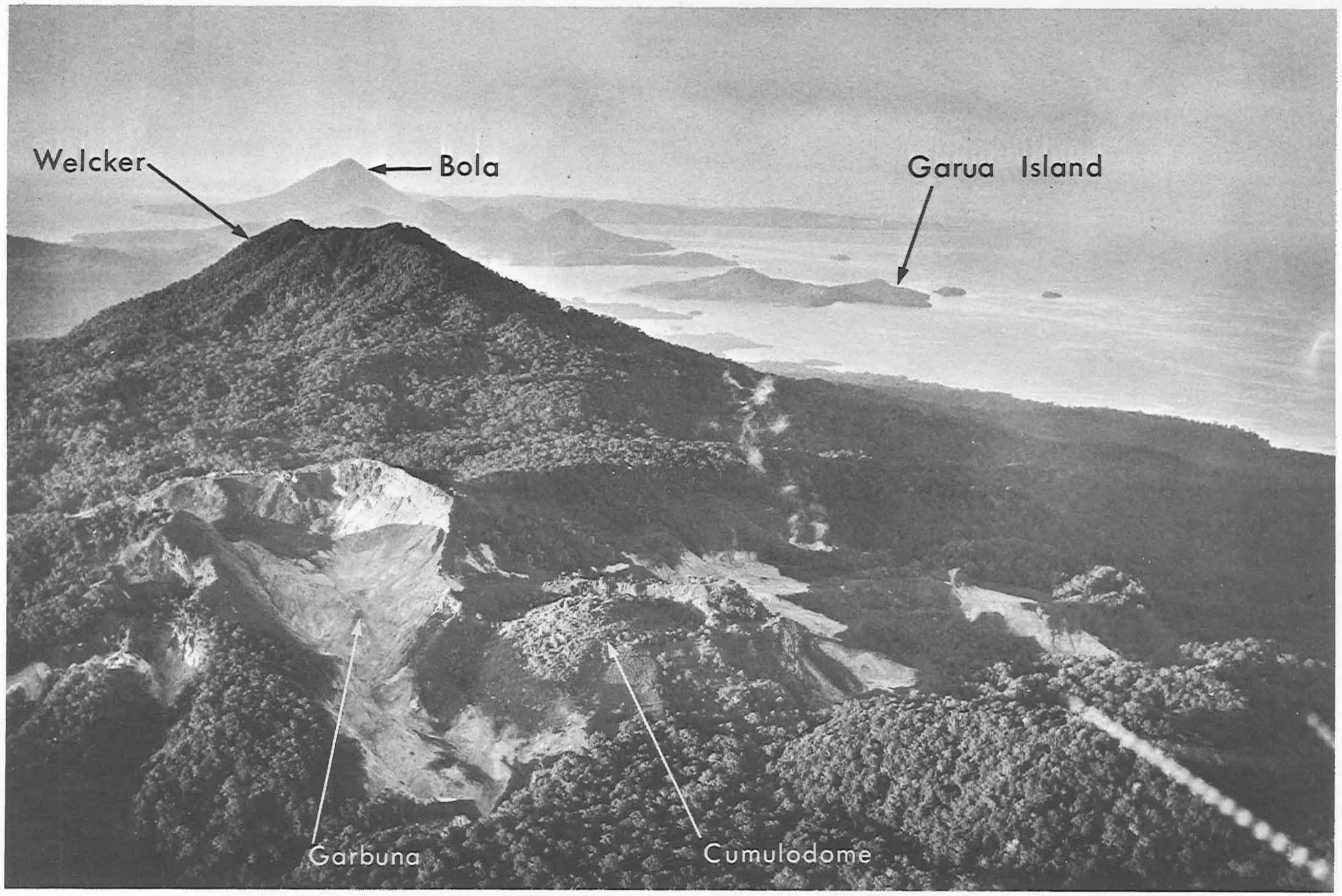


Figure 22. View northwards along Willaumez Peninsula showing the Garbuna thermal area in the foreground and Welcker volcano behind it. In the middle distance are the twin peaks of Garua Island and the prominent cone of Bola. The flat-lying rim of Dakataua caldera is visible in the far distance. Neg. No. GA/6294.

Conditions were similar in May 1969, when Johnson visited Garbuna, although no tests were made to confirm the presence of HCl and CO_2, and have probably persisted for many years prior to 1938.

The thermal activity has resulted in severe alteration of the rocks in the summit region, so that none of the samples collected for petrological study are completely fresh, and it appears that the present relatively low altitude of the summit region is due, at least in part, to solution, undercutting, and subsequent collapse of the thermally altered rocks.

One part of the Garbuna thermal area that appears to have resisted destruction by thermal activity is a prominent cumulodome in the centre (Figs 21 and 22). This dome may be younger than much of the thermal activity, and hence has suffered less alteration.

Thermal emission points are also present elsewhere in the southern Willaumez area (Fig. 21). Two small areas are south and southwest of Krummel, two others are west and southwest of Garbuna, and one hot spring is situated south of Garili village on the east coast, northeast of Welcker. Many other outlying thermal points probably exist in the area, but have not yet been located.

<u>Welcker</u> is similar in form to Krummel volcano, but is higher, rising to 1110 m above sea-level (Lae Sheet), and has an unbreached summit crater a few hundred metres in diameter. At one locality in the summit region a white, porcellanite-like rock is exposed, and this is interpreted as highly thermally altered lava; because of the forest cover the extent of this alteration is not known. No active thermal areas were found in the summit region on 13 October 1969 when Johnson climbed the eastern flank of the volcano.

Aerial photographs show the poorly defined margins of three lobate flows on the east coast of the peninsula (Fig. 21). These flows appear to have originated from Welcker, although it is not known whether they are older or the same age as the high-angle cone. Chemical analyses of samples from each of the three flows shows that the lavas are dacites. Possible flow margins in other parts of southern Willaumez Peninsula are also visible on aerial photographs, as for example, west of Garbuna, but most of these are poorly defined and are not shown in Figure 21.

The aerial photographs also show features in the eastern part of the peninsula that indicate possible faults. These are a ridge with a sinuous crest east of Gabuna, lineations west and southwest of this ridge, an arcuate scarp facing southwestwards east of Welcker, and west-facing scarps to the north. Such faults may have been formed during subsidence of the central and western parts of the Peninsula, perhaps as a result of east-west rifting or, alternatively, of slight foundering of the Krummel-Welcker volcanic line on a soft, perhaps sedimentary, basement.

Petrology

Thirty-nine rocks from the three volcanoes have been examined in thin section. Chemical analyses show that the rocks from Krummel and from the ridge to the east are basalts and low-silica andesites, whereas those from Garbuna and Welcker are high-silica andesites and dacites. The silica range of the analysed samples is 53.00 to 68.5 wt percent. Table 14 gives modal analyses of fourteen rocks, the localities of which are listed in Table 15.

Krummel. The ten rocks from the southern flank of Krummel which have been examined appear to be uniform low-silica andesites, the five chemically analysed samples having a range of silica of only 53.7 to 55.2 wt percent.

The rocks contain abundant phenocrysts of plagioclase, augite, and pleochroic orthopyroxene. Sparse olivine phenocrysts are present in a few rocks, some being rimmed by orthopyroxene or partly replaced by iddingsite. Augite and orthopyroxene phenocrysts are present in more or less equal proportions. Some augite phenocrysts are rimmed by orthopyroxene. A striking feature of the samples is the scarcity of iron-titanium oxide phenocrysts. These are present in a few rocks, mostly enclosed in silicate phenocrysts, but are absent in most samples. Minerals present in the groundmass are plagioclase, augite, orthopyroxene, low-2V clinopyroxene, and iron-titanium oxides. Sample 0282, a flow-banded weathered rock that has not been chemically analysed, has less groundmass pyroxene than the other samples and may be more silica-rich.

Ridge east of Krummel. Seven rocks from a valley cut into the ridge east of Krummel have been examined. They are similar to those of the main cone of Krummel, except that they appear to be slightly more basic. Olivine phenocrysts are more common, and chemical analyses of two rocks show lower silica values (53.0 and 53.5 wt percent), indicating basalt and low-silica andesite compositions.

The rocks are highly porphyritic, containing phenocrysts of plagioclase, augite, pleochroic orthopyroxene and, in most samples, olivine. In common with the rocks from Krummel, iron-titanium oxide phenocrysts are either absent, or present only as rare microphenocrysts. The olivine phenocrysts of several rocks are pseudomorphed by iddingsite, and in one sample the pseudomorphs are rimmed by pyroxene and oxide grains. Groundmass minerals

TABLE 14. MODAL ANALYSES OF 14 ROCKS FROM KRUMMEL, GARBUNA, AND WELCKER VOLCANOES

Group	Sample number (prefix 51NG)	Volume % phenocrysts						Total % phenocrysts
		Plagioclase	Olivine	Orthopyroxene	Augite	Fe-Ti Oxides	Amphibole	
1.	0269	19	3	2	8	(a)	-	32
	0270B	11	<1	<1	2	-	-	13
2.	0274	28	-	7	7	-	-	42
	0276	27	-	7	5	-	-	39
	0277	14	1	3	6	-	-	24
	0279	24	<1	3	3	(a)	-	30
	0283	29	-	5	2	-	-	36
3.	0145B(b)	28	-	3	6	1	-	38
	0154X	17	-	1	1	1	1	21
4.	0262(b)	8	-	<1	1	<1	-	9
	3063	26	<1(c)	4	10	1	-	41
	3064	7	-	<1	<1	<1	<1	7
	3065	23	<1	2	5	1	-	31
	4004C	26	<1	1	5	1	-	33

(a) rare microphenocrysts

(b) rock contains a few small phenocrysts of apatite

(c) pseudomorphed by orthopyroxene and iron-titanium oxides

TABLE 15. LOCALITY INDEX FOR SAMPLES OF TABLE 14, AND OF THOSE REFERRED TO IN TEXT

Group	Sample	Locality description
1. Ridge east of Krummel	0269	*in situ* lava; ca. 200 m a.s.l.) stream on
	0270B	boulder; ca. 215 m a.s.l.) eastern flank
2. Krummel volcano (southern flank)	0274	*in situ* lava flow in gully; ca. 335 m a.s.l.
	0276	boulder in gully; ca. 420 m a.s.l.
	0277	*in situ* lava in gully; ca. 410 m a.s.l.
	0279	boulder in gully, ca. 425 m a.s.l.
	0282	boulder on ridge; ca. 760 m a.s.l.
	0283	*in situ* lava near thermal area ca. 75 m a.s.l.
3. Garbuna volcano	0145B	boulder in thermal area east of summit
	0154X	bounder beneath lava outcrop in gorge southwest of summit
4. Welcker volcano	0262	boulder, eastern rim of summit crater
	3063	*in situ* lava flow, north of Kilu village) east
	3064	*in situ* lava flow, north of Patanga village) coast
	3065	in situ lava flow, north of Girili village)
	4004C) 4004D)	boulders in stream low on western flank

are plagioclase, augite, orthopyroxene, possibly low-2V clinopyroxene, and iron-titanium oxides. Tridymite is present in one rock, and cristobalite in another.

Welcker and Garbuna. The rocks examined from Welcker (12 samples) and Garbuna (10 samples) all appear to be richer in silica than those from Krummel and the eastern ridge. Olivine phenocrysts are rare and there is a relative deficiency of groundmass pyroxenes; six chemical analyses (five of rocks from Welcker and one from Garbuna) show a silica range of 59.6 to 68.5 wt percent, indicating high-silica andesite and dacite compositions.

All the samples contain, in order of decreasing abundance, phenocrysts of plagioclase, augite, pleochroic orthopyroxene, and iron-titanium oxides. A few rocks contain sparse olivine grains which in some samples are rimmed by orthopyroxene or are pseudomorphed completely by orthopyroxene and iron-titanium oxides. In one sample, 4004D, olivine grains are iddingsitised, and are rimmed by pyroxene.

Phenocrysts of hornblende are present in a few rocks, including the most silica-rich of the six analysed samples, 3064. The pleochroic scheme of hornblende phenocrysts in sample 3064 is: γ (dark brown) = β (greenish brown) > α (light brown). Small phenocrysts of apatite are also found in a few samples.

The groundmass of the Welcker and Garbuna samples is typical of silica-rich lavas. Augite and orthopyroxene are relatively deficient, compared with more basic lavas, and salic minerals are much more abundant. However, because of the very fine grain-size it is not always possible to identify the different salic minerals, which include plagioclase and probably also alkali feldspar, tridymite and cristobalite. Some samples have a heterogeneous groundmass in which light-coloured patches and lenses are contained in a darker matrix. In other rocks, the groundmass is dark, very fine-grained, and crowded with numerous grains of iron-titanium oxides.

BANGUM VOLCANO

Geology

Bangum (or Bagum) is a simple, conical, central-type volcano forming a prominent headland on the west coast of Willaumez Peninsula (Fig. 21). Remnants of a breached crater are preserved in the summit area which rises to 1050 m above sea-level (Lae Sheet). The volcano is covered by rainforest and is dissected to much the same stage as Krummel, Garbuna, and Welcker. However, unlike these volcanoes, Bangum rises as a single cone from sea-level, and does not appear to be underlain by a low-angle shield. No thermal areas have been recorded from Bangum.

Ryburn and Pieters examined outcrops on the western and southern sides of Bangum on October 21 and 22, 1969, and Pieters climbed to the summit crater. Outcrops of flow-banded lavas are common in coastal outcrops, and several of these lavas contain igneous xenoliths up to 1 m in diameter. Clastic rocks are present in at least one outcrop on the southern flank of the volcano.

Petrology

Nineteen rocks from Bangum volcano have been examined in thin section. Modal analyses of seven rocks are given in Table 16 and their localities are listed in Table 17. All nineteen samples were collected from coastal exposures, and all except one, sample 2707A, are andesites. Seven rocks have been chemically analysed: six are high-silica andesites showing a range of silica content between 59.0 and 62.4 wt percent, and the seventh, sample 2707A, is a gabbroic xenolith that has a silica content of 50.9 wt percent.

TABLE 16. MODAL ANALYSES OF 7 ROCKS

FROM BANGUM VOLCANO

Sample number (prefix 51NG)	Volume % phenocrysts					Total % phenocrysts
	Plagio-clase	Olivine	Ortho-pyroxene	Augite	Fe-Ti Oxides	
2707A(a)	38	<1	1	36	2	-
2707B	27	<1(b)	1	7	1	36
2708	26	-	2	10	2	40
2709 (c)	23	<1	2	9	2	36
2713A	26	<1	2	7	1	36
2713C	20	<1	1	8	2	31
2714C	22	-	2	7	1	32

(a) coarse-grained, gabbroic xenolith in which there is no distinction between phenocrysts and groundmass; in this analysis, all mineral grains irrespective of size have been counted; interstitial glass makes up 23 percent of the rock.

(b) aggregates of orthopyroxene and iron-titanium oxides which are assumed to be pseudomorphs of olivine

(c) this rock contains a quartz phenocryst (less than 1 percent)

TABLE 17. LOCALITY FOR SAMPLES OF TABLE 16

Sample	Locality description
2707A	xenolith in sample 2707B
2707B	in situ lava (probably a flow) at Cape Schellong, western flank
2708	in situ lava (probably a flow), western flank
2709	in situ lava flow, northwesternflank
2713A)	boulders in stream draining western flank, southeast
2713C)	of Bangum village
2714C	boulder at coast on northwestern flank

The lavas are highly porphyritic, and similar in petrography to most other Late Cainozoic andesites in New Britain. They contain phenocrysts of plagioclase, augite, pleochroic orthopyroxene, iron-titanium oxides, sparse olivine, rare quartz, and minor apatite.

Phenocrysts of augite are more abundant than those of orthopyroxene, some of which are rimmed by augite. Olivine phenocrysts are present in a few rocks, but not in amounts greater than about 1 percent. Some olivine grains are euhedral, some are rimmed by pyroxene and iron-titanium oxides, some are iddingsitised, and some are pseudomorphed by orthopyroxene and iron-titanium oxides.

The groundmass of most samples is very fine-grained. Plagioclase and iron-titanium oxides are the most common minerals. Augite and orthopyroxene are present in smaller amounts, but are clearly identified only in rocks that have a coarser than average groundmass. Several rocks have heterogeneous groundmass textures typical of siliceous rocks, similar to those described from Welcker and Garbuna volcanoes. Cristobalite and tridymite are present in a few rocks and some interstitial patches have been tentatively identified as alkali feldspar.

Sample 2707A, a xenolith contained in a lava flow (sample 2707B), is a coarse-grained rock composed mainly of plagioclase and augite showing sector and oscillatory zoning, accompanied by iron-titanium oxides, pleochroic orthopyroxene (some of which is rimmed by augite), apatite, and interstitial vesicles and brown glass.

DISCUSSION

Descriptions of the volcanic geology, thermal activity, and petrology of Willaumez Peninsula north of Bangum volcano have been given by Stanley (1923), Fisher (1939, 1957), Reynolds (1954b), Branch (1965, 1967), Heming & Smith (1969), Heming (1969) and, in particular, by Lowder & Carmichael (1970) and Lowder (1970). Because of this previous work, the 1969 BMR field party did not survey the volcanoes on this part of Willaumez Peninsula. A list of the volcanoes, but no descriptions, are given below. However, it is planned to present in a later report summary accounts of these volcanoes and their petrology and to compare them with other Late Cainozoic volcanoes in New Britain.

Two aspects of the general geology of Willaumez Peninsula are briefly discussed here: firstly,the evolution of the Peninsula by the progressive migration of eruptive centres; and secondly, the abundance of acid rocks in the central part of the Peninsula.

The volcanoes of the northern half of Willaumez Peninsula can be grouped as follows*: (1) in the south, a series of minor centres consisting predominantly of coulees and cumulodomes formed of high-silica dacite and rhyolite; these partly encircle Garua Harbour; (2) Lotomgan, Tolokemba, and Luligi volcanoes further north; (3) Bola, a steep-sided conical volcano at whose summit Stanley (1923) reported seeing emissions of water vapour in 1921; (4) Dakataua caldera at the northern end of the Peninsula, containing Lake Dakataua and Makalia volcano.

From a consideration of their relative degrees of dissection and published reports of volcanic activity, it appears that, in general, the volcanoes of Willaumez Peninsula become progressively younger northwards. Dufaure, the southernmost volcano, is also the most deeply dissected. Krummel, Garbuna, Welcker, and Bangum volcanoes are much less dissected, but they appear to be more deeply eroded than any of the

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* For geological maps of northern Willaumez Peninsula, see figure 1 in Lowder & Carmichael (1970), and BMR Talasea-Gasmata 1:250 000 map (preliminary edition).

volcanoes further north. Krummel, Garbuna, and Welcker rise from a broad, low-angle shield that was probably an active volcano before the volcanoes of northern Willaumez Peninsula were built up. Makalia at the northern end of the Peninsula appears to be the most recently active centre, and is thought to have erupted in the late nineteenth century (Branch, 1967). Bola, immediately southwest of Makalia, may also be classified as an active volcano if its summit thermal activity (Stanley, 1923; Lowder & Carmichael, 1970) is taken to indicate a potential for further eruptions (Fisher, 1957). Tolokemba, Luligi, Lotomgan, and Humugari volcanoes, all south of Bola, appear to be older than Bola 'on the basis of more advanced erosion' (Lowder & Carmichael, 1970).

Extinction of volcanic activity along the Peninsula therefore appears to have taken place firstly in the south, and to have moved progressively, though not necessarily regularly and systematically, northwards. A similar northward migration of eruptive centres was suggested by Johnson, Davies & Palfreyman (1971) in the Cape Gloucester area at the western end of New Britain (Fig. 1). Both lines of volcanoes are at right angles to the east-west axis of New Britain, and may indicate underlying north-south fractures that were propagated northwards.

Lowder & Carmichale (1970) mapped most of the rocks surrounding Garua Harbour in the Talasea area as 'rhyolite and rhyodacite lava', containing more than 70 wt percent silica. These lavas were erupted from several centres, the most important of which are Garua Island (two centres), Schleuther, Big Mount Worri, Humugari (or Little Mount Wori), Big Gulu, and Little Gulu. These centres, which are arranged in a roughly ring-like pattern, appear to have been responsible for the extrusion of most, if not all, of the high-silica dacite and rhyolite lavas on Willaumez Peninsula.

The ring-pattern of the Talasea centres and the abundance of acid lava is strongly reminiscent of the volcanic St Andrew Strait Islands in the northern Bismarck Sea area (Fig. 1; Johnson & Davies, 1972). The St Andrew Strait Islands trend north-northeast, oblique to the east-west northern margin of the Bismarck Sea and comparable in orientation to Willaumez Peninsula. Acid rocks are abundant on the central islands of the St Andrew Strait chain, and form the entire exposed part of Lou, the largest island, where there are twelve principal centres of acid volcanism. These centres define a prominent arc which, according to Johnson & Davies (1972), may be part of a ring fracture along which cauldron subsidence might take place in the future. By analogy, the acid centres of the central part of Willaumez Peninsula may also mark a possible site for future cauldron subsidence. However, if the peninsula has grown by the northward migration of volcanic centres, new eruptive sites would be expected north of the Dakataua area. Hence the possibility of future eruptions and of cauldron subsidence in the Talasea area is much less than in St Andrew Strait.

PART 4: WITU ISLANDS

INTRODUCTION

The volcanoes of the Witu, or French Islands are of considerable petrological interest, as they are further from the axis of the New Britain submarine trench than the New Britain volcanoes, and they overlie the deepest part of the New Britain Benioff Zone (Fig. 1). Because compositions of volcanic rocks are, in many cases, related to the depth of an underlying Benioff Zone, the rocks of the Witu Islands can be expected to be chemically distinct from those on mainland New Britain.

The Witu group consists of four principal islands, Garove, Unea, Mundua, and Narage, and five smaller islands off the west end of Mundua (Fig. 23). There are also three isolated areas of coral reefs. The most extensive is Ottilien Reefs in the extreme west, which partly break sea-level to form Sand Island. A second area, Widu Reef, lies between Garove and Mundua Islands, and is reported to break surface at low tide (AGS, 1943). Both these areas of reefs are probably built on volcanic foundations. The third area is west of Unea Island. Coral also forms fringing and offshore reefs around all the volcanic islands.

With the exception of Unea Island in the south, the Witu Islands and Ottilien Reefs lie within a zone 80 km long and 10 km wide, which can be extrapolated 170 km eastwards to join the volcanic zone containing Banban Island, Lolobau Island, and Likuruanga volcano in New Britain (Fig. 1, and Johnson, 1970c). This alignment may be fortuitous, especially as the extrapolation is over a long distnace, but it may indicate a major structural feature, with associated volcanism at either end, crossing the southeast part of the Bismarck Sea. However, except for Unea, the Witu

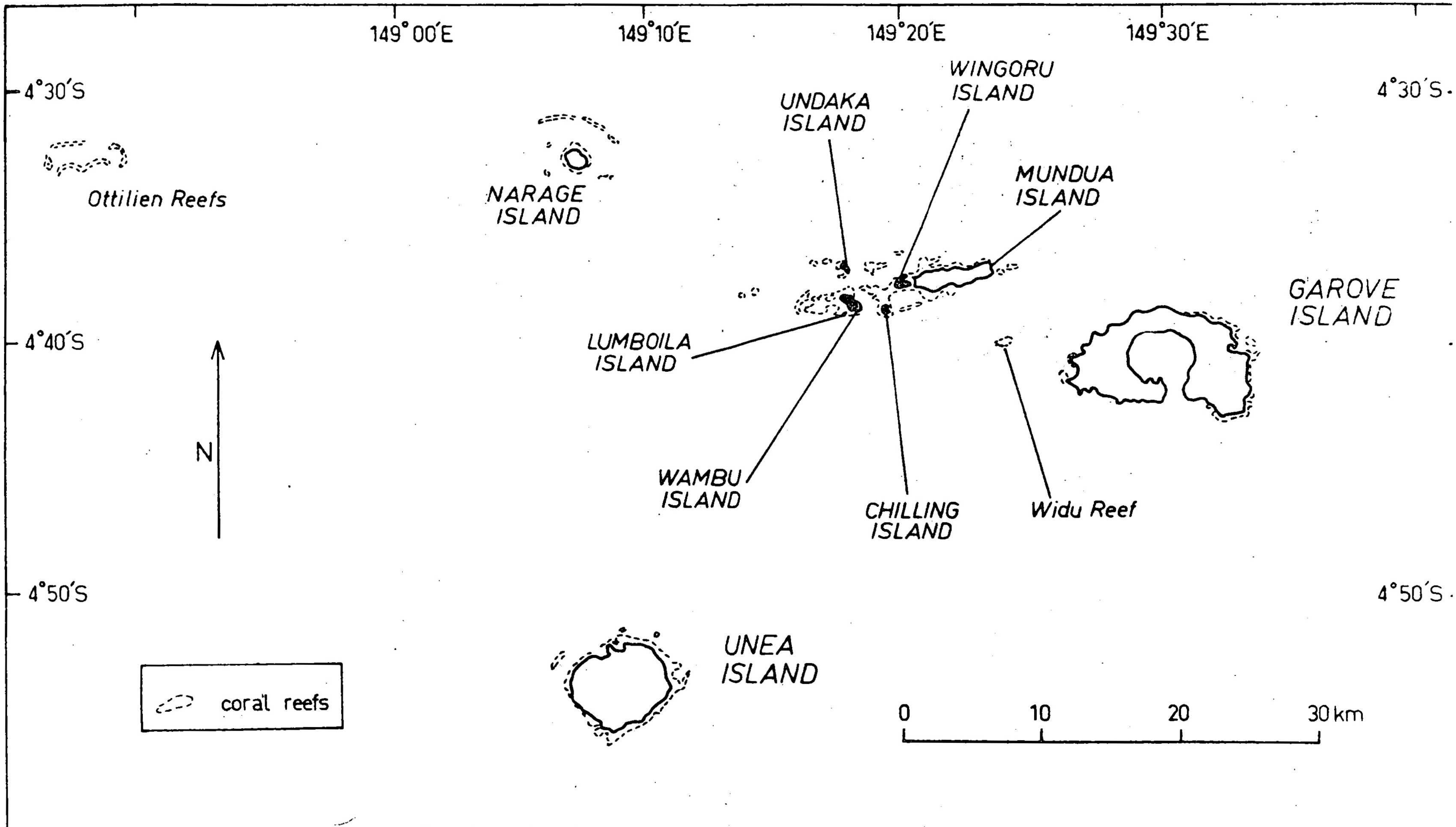

Figure 23. Locality map of Witu Islands

To accompany Record 1972 133

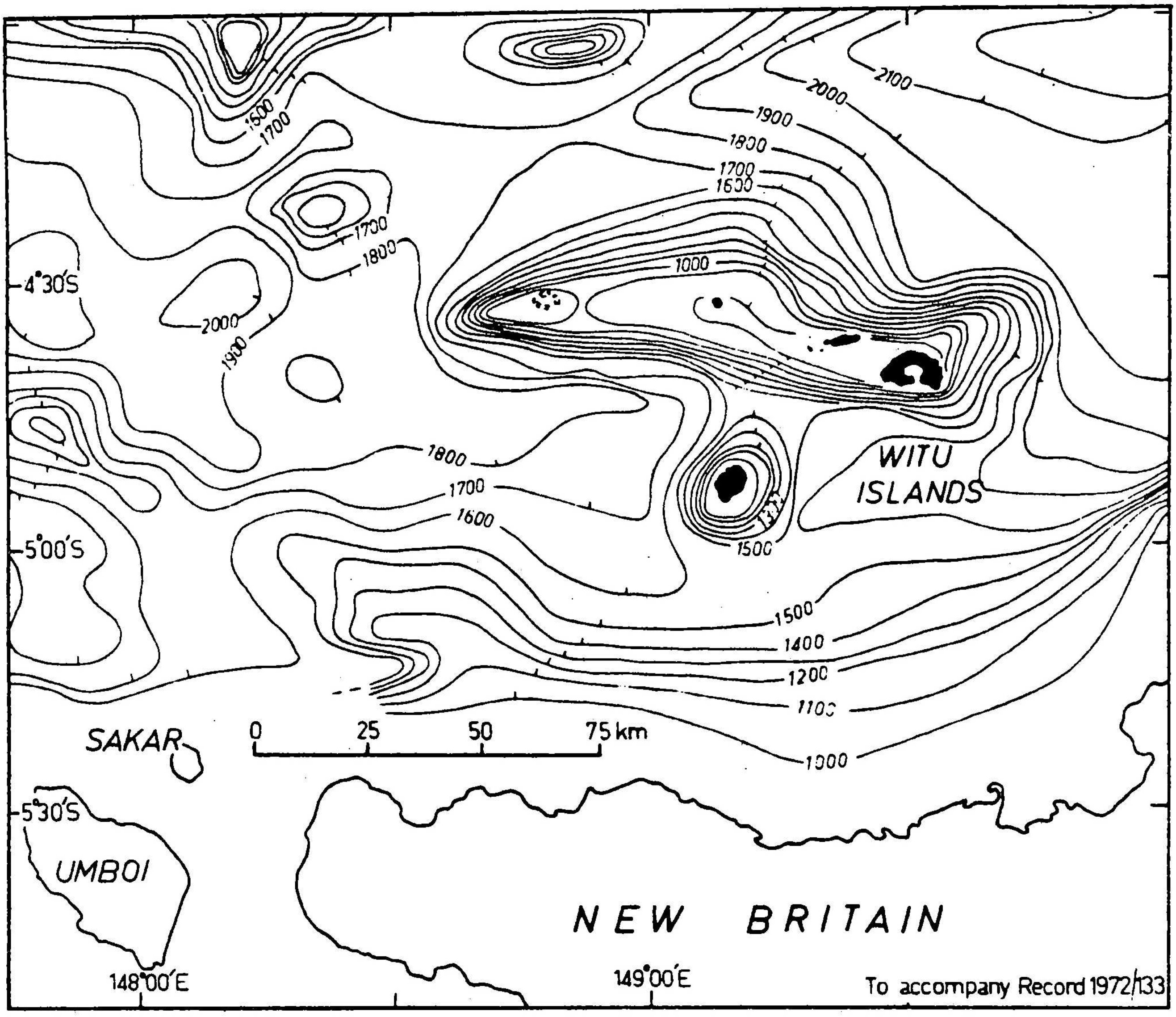

Fig. 24. Bathymetry in the vicinity of the Witu Islands. Adapted from unpublished data obtained by B.M.R. Bismarck Sea Marine Geophysical Survey (1970). Depths in metres. Dashes on deeper side of bathymetric contours.

Islands lie on a narrow submarine ridge which drops into deep water at its eastern and western ends, and there appears to be no submarine topographic feature that links the ridge with the Banban-Lolobau-Likuruanga zone (Fig. 24).

The bathymetry of the Bismarck Sea* also shows that the Witu Islands rise from a broad submarine ridge that extends northwestwards across the Bismarck Sea from Willaumez Peninsula to the St Andrew Strait Islands south of Manus Island (Fig. 1). Circular Reef, Sherburne Reef, the Purdy Islands, and Alim Island also rise from this ridge northwest of the Witu Islands. This ridge possibly represents a submarine volcanic zone.

The Witu Islands and Ottilien Reefs lie opposite a section on New Britain Island, between the Cape Gloucester area and Willaumez Peninsula, where there appears to have been little, if any, late Quaternary volcanism (Fig. 1). Older volcanic rocks (Plio-Pleistocene) make up Mounts Andewa and Schrader in the western part of the section, and are also thought to be associated with Mount Penck in the eastern part, but in between there is a low-lying stretch of land with no volcanoes. The Witu Islands could therefore be thought of as a section of the New Britain Quaternary volcanic arc which has a northward 'off-set'. However, there is no evidence for such an off-set being bounded by transcurrent faults.

The depth of the Benioff Zone beneath the Witu Islands is not known precisely since very few seismic events from the deep parts of the Zone have been accurately located. Only two events in the Witu region were used in the description of seismicity given by Johnson (1970b): these had depths of 565 and 382 km, the former being the deepest event recorded in Papua New Guinea up to June 1969. However, both seismic events, in

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* See, for example, the 1:2 500 000 map of Papua New Guinea (Division of National Mapping, Canberra, 1970).

conjunction with the known seismicity of the remainder of the Bismarck Volcanic Arc, leave little doubt that the Witu Islands overlie the deepest part of the northward-dipping New Britain Benioff Zone.

Progressive northward increases in K_2O and $Na_2O + K_2O$ contents have been recognized in the volcanoes of New Britain for rocks with the same silica content, and have been corellated with increasing depth to the underlying Benioff Zone (Johnson, Mackenzie, & Smith, 1970, 1971). Further increases in $Na_2O + K_2O$ content for equivalent silica values are shown by three of five rocks from the Witu Islands for which chemical analyses are available; the remaining two samples have values about the same as rocks from the northern part of Willaumez Peninsula. However, the five Witu samples do not show increases in K_2O content: four have K_2O values similar to rocks with the same silica content from northern Willaumez Peninsula, and the fifth has a value only slightly higher.

Two other distinctive chemical features are shown by the analysed Witu rocks. The first is that two of the samples have P_2O_5 contents of 0.39 and 0.40 wt percent. These values are much higher than those of analysed rocks from volcanoes in New Britain, most of which contain less than 0.2 wt percent P_2O_5. Secondly, all five samples contain over 1.0 wt percent TiO_2, in contrast with analysed rocks from other Late Cainozoic volcanoes in the southern Bismarck Sea area, which mostly contain less than 1 wt percent TiO_2. The highest TiO_2 content is 1.91 wt percent, in an olivine tholeiite. This TiO_2 value is similar to those of many oceanic basalts (Chayes, 1965).

UNEA ISLAND

Introduction

Unea, also known as Bali Island, is the most southerly of the Witu Islands (Fig. 23). It is roughly circular (Fig. 25), and the highest point is Mount Kumbu, in the centre of the island, which is about 590 m above sea-level (according to the German Admiralty chart, 1909). The island is heavily populated, and there are fourteen principal villages. Bali plantation covers an extensive flat area in the west, a Roman Catholic Mission (Unea) is situated on the north coast. Coral reefs fringe the entire coastline, and form small patches off-shore.

No previous descriptions of the geology and petrology of the island have been made.

Geology

Unea consists of the remnants of a caldera, and three principal post-caldera volcanoes (Figs 25 and 26), all of which are extinct. The volcanic rocks are low-silica andesites and basalts containing variable amounts of phenocrysts.

Pre-caldera rocks are found on two narrow arcuate ridges in the western and northeastern parts of the island (Fig. 25). The concave sides of the ridges have mostly steeper slopes than the convex sides, and they are interpreted as the remnant walls of the caldera. Originally, the caldera must have had a diameter of about 6 km, similar to the caldera on Lolobau Island (Johnson, 1970c) but smaller than many other calderas in the southern Bismarck Sea area. The missing southeastern half of the caldera escarpment has presumably been destroyed by marine

Figure 25 Unea Island. Contours (50m intervals) adapted from German Admiralty chart (1909)

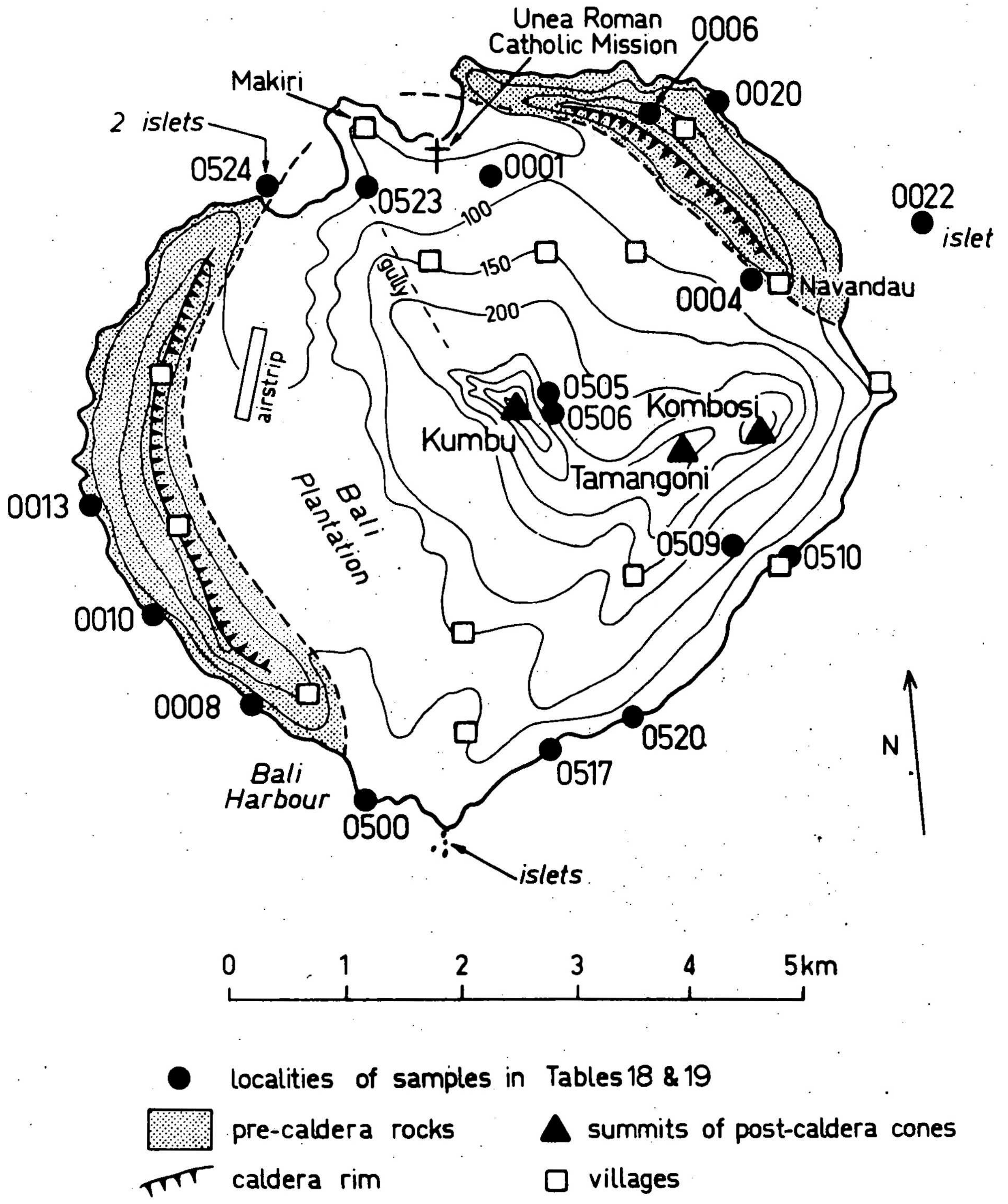

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Figure 26. Unea Island from the southeast, showing the caldera rim on left and extreme right, and the three post-caldera volcanoes Kumbu (left), Tamangoni (centre), and Kombosi (right). Neg. No. GA/6233.

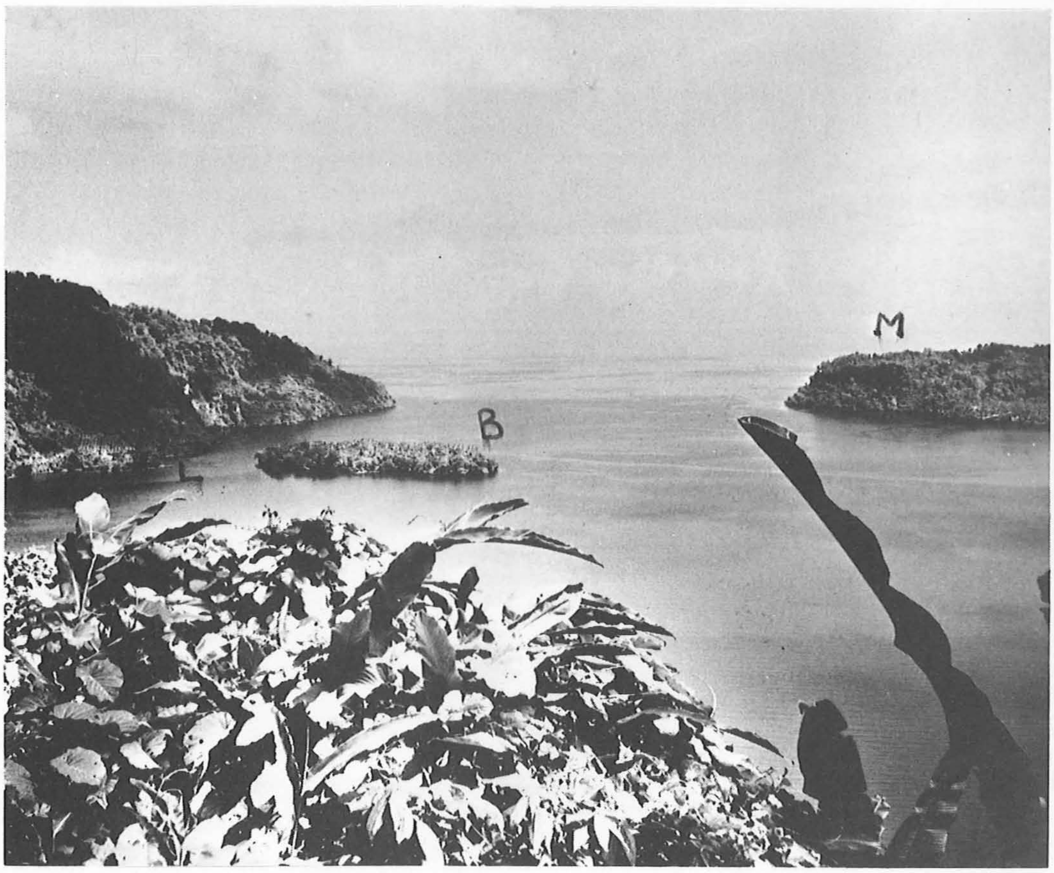

Figure 27. Entrance to Johann Albrecht Harbour, Garove Island, from the northern rim of the caldera looking south, showing littoral shelf (L) and Benukanakare Island (B) in the east, and the mission peninsula (M) in the west. Neg. No. GA/5931.

erosion. In the north, the sea has also breached the caldera escarpment to form two prominent bays on either side of the peninsula upon which Makiri village is built (Fig. 25).

The remnant caldera walls are covered by vegetation, and exposures of the pre-caldera rocks are mainly confined to the coast. On the west coast, cliffs up to 25 m high show a single columnar-jointed lava flow. On the northwest coast, a 6 m-thick massive bed of oxidized scoriae, spindle bombs, and welded spatter suggests the presence of a nearby eruptive centre. Flow-banded lava flows are exposed at other points along the coastline.

Rocks produced by post-caldera activity make up the greater part of the surface area of Unea, and form the high central peaks of the island. Three principal post-caldera volcanoes are preserved. These are Kumbu, the highest cone, which rises to 590 m above sea-level in the centre of the island; and Tamangoni, 500 m, and Kombosi (also known as Kumburi), 462 m, in the southeast, where their southeastern flanks drop steeply to sea-level (Fig. 26). No summit craters are present on any of the three volcanoes. The cones are not deeply dissected, although there is a prominent gully on the northwestern flank of Kumbu which runs in an almost straight line from near the summit of the volcano to the bay west of Makiri village. This gully may be fault-controlled. There is also a deep gully on the south flank of Kombosi which has cut back to the summit, forming an ampitheatre-like headwall (Fig. 26).

The post-caldera volcanoes are covered by vegetation, and there are few good exposures. Rock outcrops observed in 1970 on Kumbu and Tamangoni were of massive, columnar-jointed lava forming cliffs up to 30 m high, indicating that either or both thick coulées and cumulodomes make up at least part of the volcanoes. Further evidence for this is given by the slopes of the cones, which are partly convex like the flanks of cumulodomes. However, in other parts of the island, some post-caldera lava flows are thinner; for example, a lava flow 5-6 m thick is well-exposed behind the wharf at Bali Harbour. These lavas may represent more extensive fluid flows pre-dating the eruption of the more viscous extrusions that formed the post-caldera volcanoes.

Petrology

Fifty-one rocks from Unea Island have been examined in thin section, and fifteen modal analyses have been made (Table 18). Table 19 lists the localities of the fifteen samples, which are divided into pre- and post-caldera groups.

Unea rocks are porphyritic, but generally less so than rocks from the volcanoes on New Britain. As shown in Table 18, some rocks have more than 30 percent phenocrysts, but others, for example 0020, are almost aphyric. Olivine phenocrysts are present in most samples, and the rocks probably range from basalt to low-silica andesite. Chemical analyses of two olivine-free samples, 0013 and 0022, show silica contents of 53.7 and 57.5 wt percent, indicating low-silica andesite compositions.

In common with the late Cainozoic volcanic rocks in New Britain, plagioclase is the most common phenocryst, but in no sample from Unea does it exceed 30 percent of the total rock volume. The plagioclase phenocrysts show complex zoning and contain mineral grains and inclusions. They commonly form aggregates with other phenocryst minerals. The compositions of plagioclase phenocrysts in pre-caldera sample 0010 are An 71, 71 80, 79, and 77 (bytownite). In samples 0505 and 0506, both post-caldera rocks, plagioclase compositions are An 68, 48, 59, and An 59, 69, 71, respectively (mainly labradorite).

Augite phenocrysts are present in all the samples, and in several they make up between 10 and 15 percent of the rock. They are most abundant in olivine-rich samples.

Pleochroic orthopyroxene phenocrysts are commonly present in post-caldera rocks (group 2) but are rare in pre-caldera rocks (group 1). This is perhaps due to most of the post-caldera rocks being slightly more siliceous, as indicated by the plagioclase compositions given above, than the pre-caldera rocks. No rock contains more than 1 percent orthopyroxene phenocrysts, and in some only a few small grains are present. Orthopyroxene is rimmed by augite in some rocks, and is present as cores of augite phenocrysts in sample 0500.

Olivine phenocrysts are present in most samples, but are rare or absent in those that are sparsely porphyritic. In most samples, the olivine is at least slightly altered, and in a few is replaced by 'iddingsite'. Most olivine phenocrysts do not have coronas of pyroxene or iron-titanium oxide, and in this respect are similar to those in many of the olivine -rich lavas from volcanoes off the north coast of New Guinea (Johnson, Taylor, & Davies, 1972). In a few samples, however, narrow coronas of orthopyroxene are developed, in one sample, 0524, olivine phenocrysts have narrow coronas of augite, in sample 0517 coronas of iron-titanium oxides are developed, and two samples, 0001 and 0506, contain aggregates of orthopyroxene and iron-titanium oxide which appear to be pseudomorphs after olivine.

Iron titanium oxide phenocrysts are present in most rocks, except those rich in olivine, but rarely exceed 1 percent. Sparse microphenocrysts of apatite are also present in many rocks.

The groundmass of most Unea samples is glassy or very fine-grained. The most readily recognised minerals are plagioclase, iron-titanium oxides, and pyroxene. In rocks which are coarser grained the groundmass pyroxenes can be identified as augite, orthopyroxene, and low-2V clinopyroxene.

Groundmass orthopyroxene appears to be most common in those rocks of group 2 that contain orthopyroxene phenocrysts. Olivine is present in the groundmass of some rocks containing several percent olivine phenocrysts. Tridymite and cristobalite are present in some vesicles.

GAROVE ISLAND

Introduction

Garove Island, also known as Witu, Vitu, or Widu, is the largest of the Witu Islands (Fig. 1), and covers about 50 km^2 (Fig. 28). The highest point on the island (according to the German Admiralty chart) is 350 m above sea-level, on the southeastern side of a 5 km-wide central caldera. Formation of a narrow breach in the south caused the sea to flood the caldera, forming Johann Albrecht Harbour (Figs 27 and 28). Coral reefs fringe most of the northern and eastern coastline but are poorly developed in the west and along the south coast.

The outer flanks of Garove Island mostly slope at less than 10^{o}, except where they are interrupted by steep-sided satellite cones.

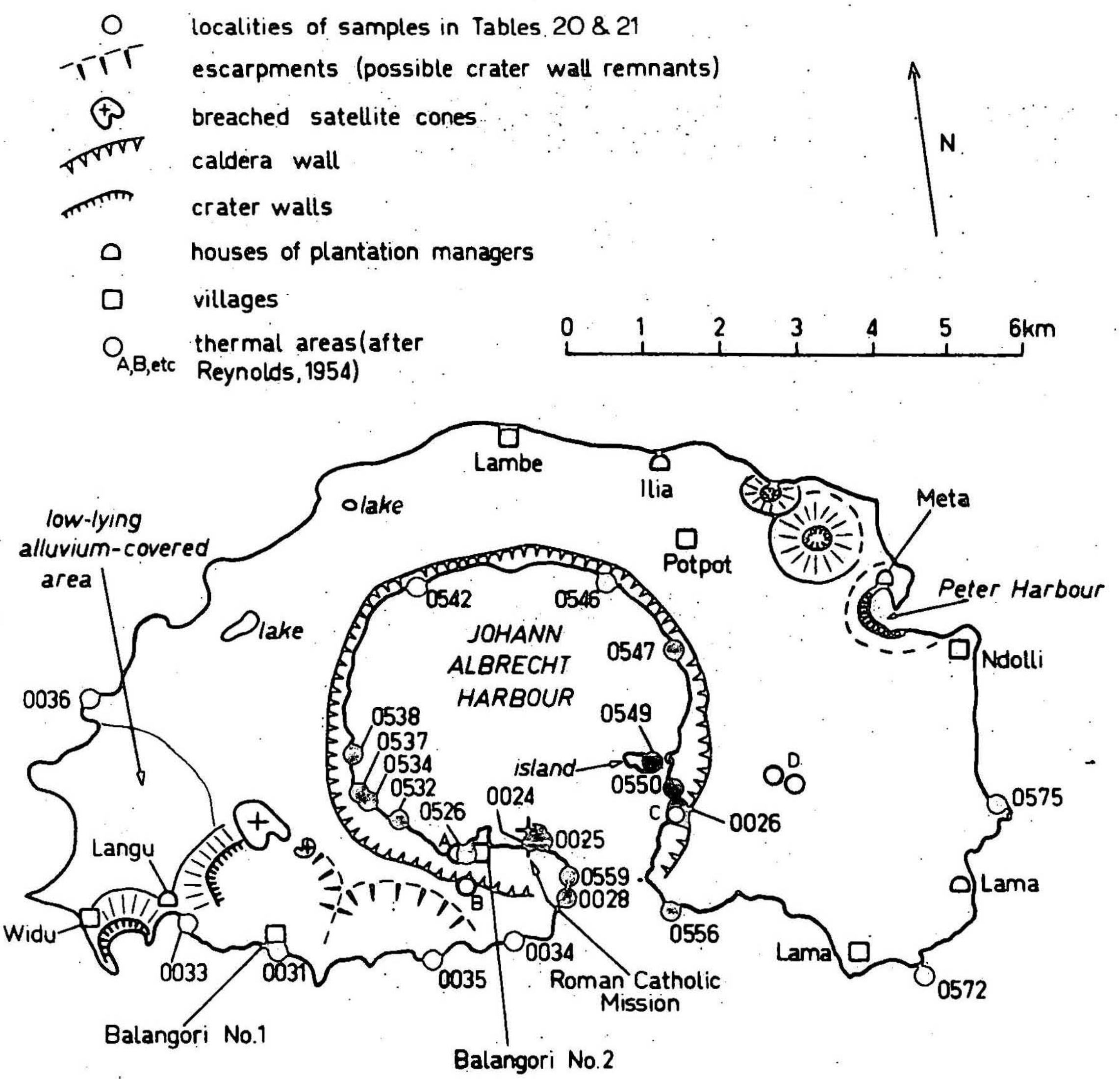

Figure 28. Garove Island. Adapted from German Admiralty chart (1909) and aerial photographs taken 6/7/66

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TABLE 18. MODAL ANALYSES OF 15 ROCKS FROM UNEA ISLAND

Group	Sample number (prefix 48NG)	Volume % phenocrysts					Total % phenocrysts
		Plagioclase	Olivine	Ortho-pyroxene	Augite	Fe-Ti oxides	
1.	0006	12	9	-	13	-	34
	0008	4	-	-	<1	<1	4
	0010(a)	29	1	-	3	2	35
	0013	1	-	-	<1	<1	1
	0020	<1	-	-	<1	<1	<1
	0022(b)	61	3	-	11	1	76
2.	0004	6	-	<1	1	<1	7
	0500(c)	17	3	1	14	1	36
	0505	28	1	1	7	1	38
	0506	24	2	1	9	1	37
	0509	7	<1	<1	2	<1	9
	0510	11	<1	1	2	1	15
	0517	13	<1	<1	5	1	19
	0520	19	<1	1	6	1	27
	0523	31	1	1	5	<1	38

(a) coarse-grained groundmass in which plagioclase laths are prominent; many of these have been counted as microphenocrysts

(b) coarse-grained sample in which there is no distinction between phenocrysts and 'groundmass'; in this analysis, all mineral grains, irrespective of their size, have been counted, except for 24 percent indeterminate interstitial materials.

(c) coarse-grained groundmass containing large grains, some of which have been counted as microphenocrysts

TABLE 19. LOCALITY INDEX FOR SAMPLES OF TABLE 18 AND OF THOSE REFERRED TO IN TEXT

Group	Sample	Locality description
1. Pre-caldera rocks	0006	loose block on northeastern rim of caldera.
	0008, 0010	beach boulders, southwestern coast.
	0013	in situ lava, columnar-jointed flow exposed in 25 m-high cliff on west coast.
	0020	in situ lava on northeastern coast.
	0022	beach boulder, north side of islet off northeastern coast (probably on outlier of pre-caldera volcano).
2. Post-caldera rocks	0001	boulder in stream 250 m east of Catholic Mission.
	0004	boulder in stream west of Navandau village.
	0500	in situ lava flow, 4 m thick, Bali Harbour wharf.
	0505	in situ lava, 30 m-high cliff, east flank of Kumbu.
	0506	same lava mass as 0505, exposed in 15 m high cliff.
	0509	talus boulder, southeastern flank of Tamangone.
	0510	talus boulder, southeastern flank of Kombosi.
	0517	in situ fissile lava, southeastern coast.
	0520	in situ columnar-jointed lava, southeastern coast.
	0523	in situ flow, south of Makiri village.
	0524	in situ flow, islet off northwestern coast.

The flanks are generally uniform and are not deeply incised. This suggests that activity from the main eruptive centres on Garove Island ceased relatively recently, and also that the caldera may be a comparatively young feature, perhaps less than one thousand years old. The lavas on Garove are generally sparsely porphyritic and probably range in composition from basalt to dacite.

Because Garove is neither deeply dissected nor steep-sided, much of it has been utilized for copra production, and there are four plantations on the island. The western plantation, Langu, occupies a flat low-lying coastal area consisting mainly of alluvium (Fig. 28).

On Garove there are seven villages and a Roman Catholic mission whose station is built on a small peninsula overlooking Johann Albrecht Harbour (Figs 27, 28 and 29). On the western side of the mission peninsula there is a sheltered wharf. A second wharf at Peter Harbour on the east coast serves the four plantations.

No published information is available on the geology and petrology of Garove, but thermal areas were described by Reynolds (1954a; see also Fisher, 1957), and brief descriptions of volcanic landforms were given by Fisher (1939, 1957).

Main volcano

Garove Island is a simple central-type volcano on whose flanks several satellite cones were built. Rocks of the main volcano are best exposed in the walls of the central caldera and, to a lesser extent, along the southern and possibly western coasts. Very few exposures

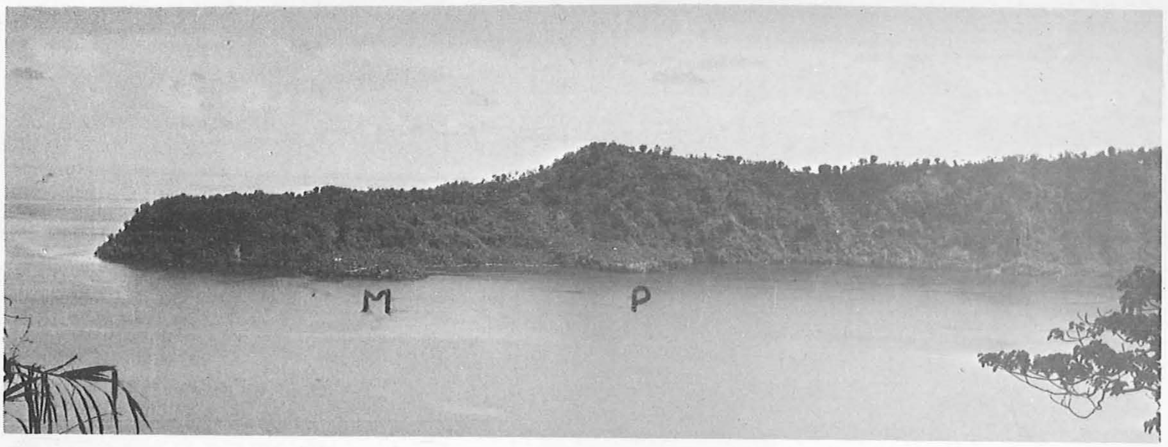


Figure 29. Southwestern side of Johann Albrecht Harbour, Garove Island, from the northwest, showing entrance to harbour on the extreme left, and the mission peninsula (M) and second peninsula (P). Neg. No. M/1104.

Figure 30. View northwards from thermal area C (cf. figure 29) on southeastern side of Johann Albrecht Harbour, Garove Island, showing the southern end of a narrow shelf (L), Benukanakare Island (B), and the northern caldera wall. Neg. No. M/1104.

of the main volcano are found along the northern and eastern coastline.

Lava flows, pyroclastic deposits, well-bedded sediments consisting of volcanic debris, and dykes are all conspicuous in the caldera wall. Single lava flows commonly form cliffs over 15 m high, and in the higher parts of the caldera wall some flows are up to 30 m thick. Columnar-jointing is common, and a sub-horizontal platy jointing is found in some outcrops. At sample point 0559 (Fig. 28), a lava flow contains numerous pale relatively coarse-grained xenoliths, some several centimetres in diameter.

Clastic rocks crop out at sea-level in the caldera wall, where they consist of massive, crudely bedded, scoriaceous layers, and sequences of well-bedded volcanic deposits. Scoriaceous and other rudaceous deposits are especially abundant in the southeastern part of the caldera, and in the eastern cliffs at the entrance to Johann Albrecht Harbour. In one exposure examined these deposits are intercalated with lava flows.

The well-bedded clastic rocks crop out in the southwestern, northwestern, and southeastern parts of the caldera. They consist of rudites, arenites and lutites, some of which show current bedding and graded bedding. Some beds are unsorted and consist of lava clasts up to several centimetres across enclosed in a very fine matrix. In places the beds are gently warped. The well-bedded deposits are overlain by a lava flow at one locality in the northwest, and in the southeast, similar beds are faulted against scoriae and lava flows. These well-bedded clastic deposits were probably laid down in water.

Numerous near-vertical dykes are exposed in the caldera wall, particularly in the southeast and southwest. For example, in a section between sample points 0534 and 0537 (Fig. 28), nine dykes are exposed. The dykes which trend southeastwards are mostly less than 1 m but range up to 3 m wide. They have chilled margins and show crude jointing perpendicular to their contacts. Well-bedded clastic deposits which they intrude are baked.

Normal faults are exposed in several parts of the caldera wall, and there are numerous faults in the cliff on the east side of the entrance to Johann Albrecht Harbour. In no case could the amount of movement along a fault be estimated, because of the lack of marker horizons.

Outside the caldera most coastal exposures are of rocks that appear to have been erupted from satellite centres. However, lava flows and beds of volcanic arenaceous and rudaceous deposits belonging to the main volcano are found along the south coast east of the harbour entrance.

On the northwest coast there are several prominent rounded headlands of lava, which may be flow fronts. Sample 0036 (Table 20 and Fig. 28) was collected from one of the headlands. The exposed lavas have spinose and flat scoriaceous surfaces, and deep clefts formed by rupture during flow (Fig. 31). The preservation of these structures suggests that the lava flows may be only a few hundred years old. The source of the flows could not be located on aerial photographs. The flows may be the youngest on the main volcano,

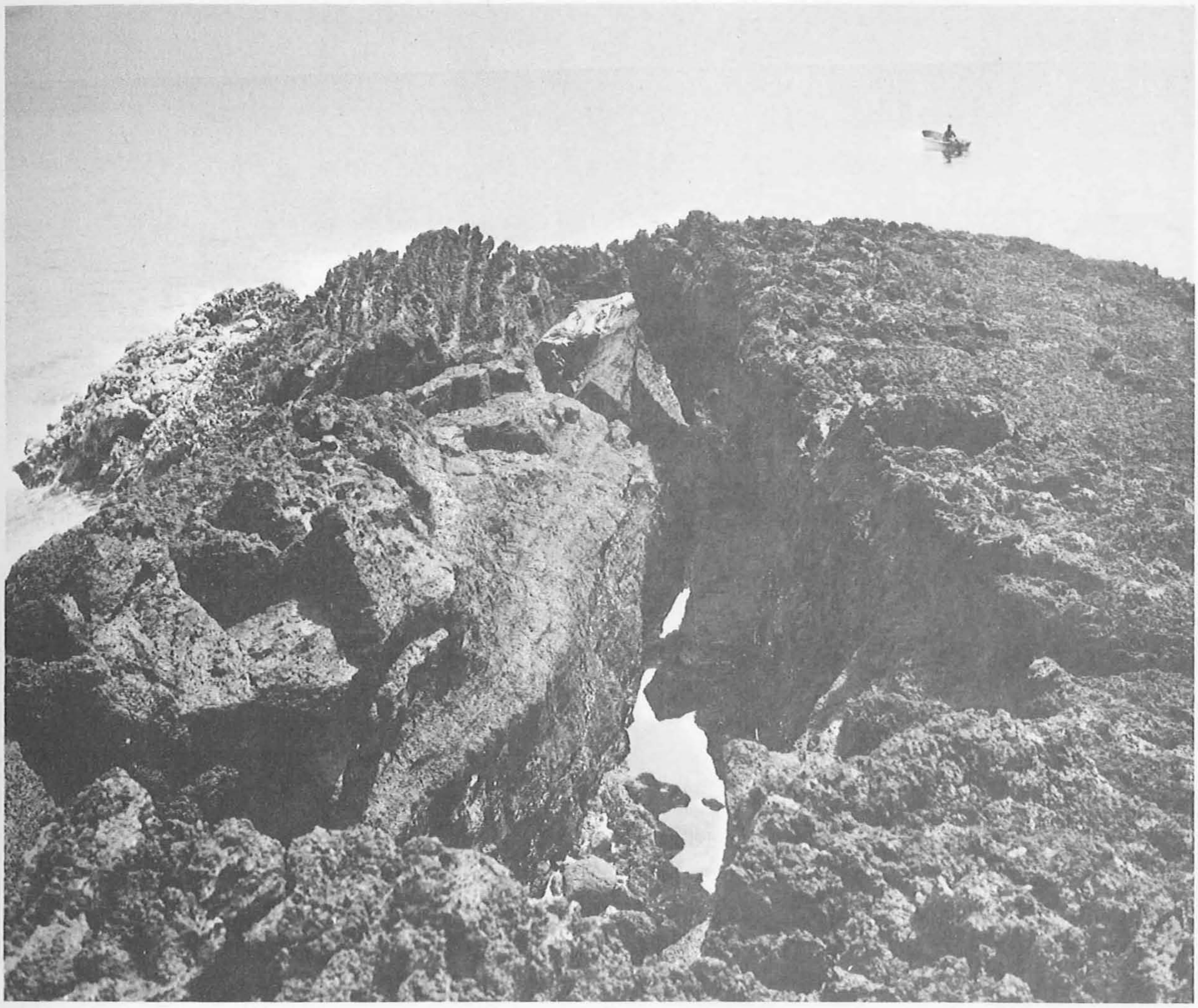


Figure 31. Surface of lava flow exposed on west coast of Garove Island, showing a large tension gash between a scoriaceous surface on the right, and a rilled scoriaceous surface on the left. Neg. No. M/1104.

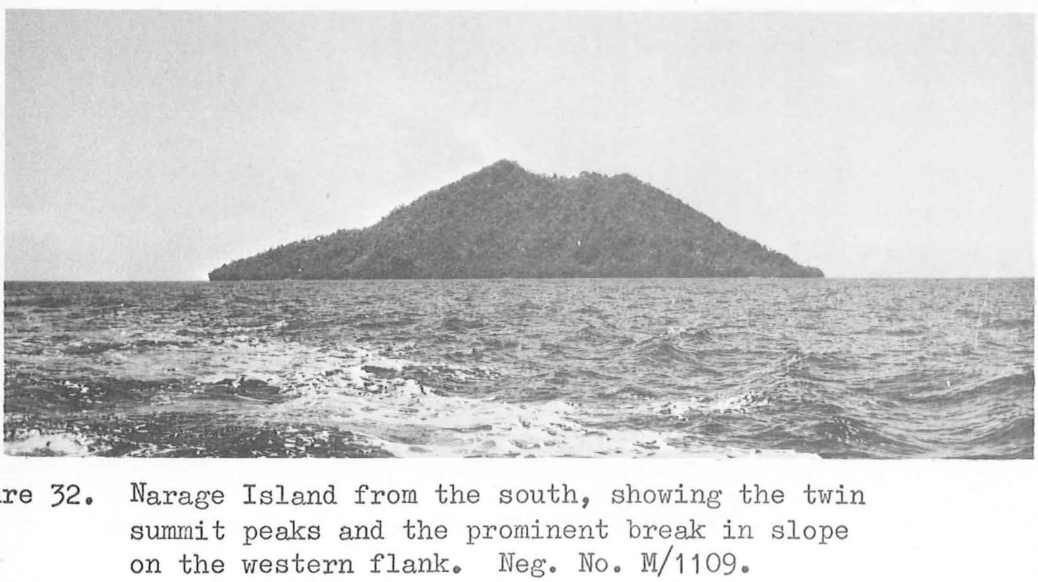


Figure 32. Narage Island from the south, showing the twin summit peaks and the prominent break in slope on the western flank. Neg. No. M/1109.

erupted from summit vents which were later engulfed by cauldron subsidence. However, because of their very young appearance, it is more likely that they originated from inconspicuous satellite vents on the western flank of the island.

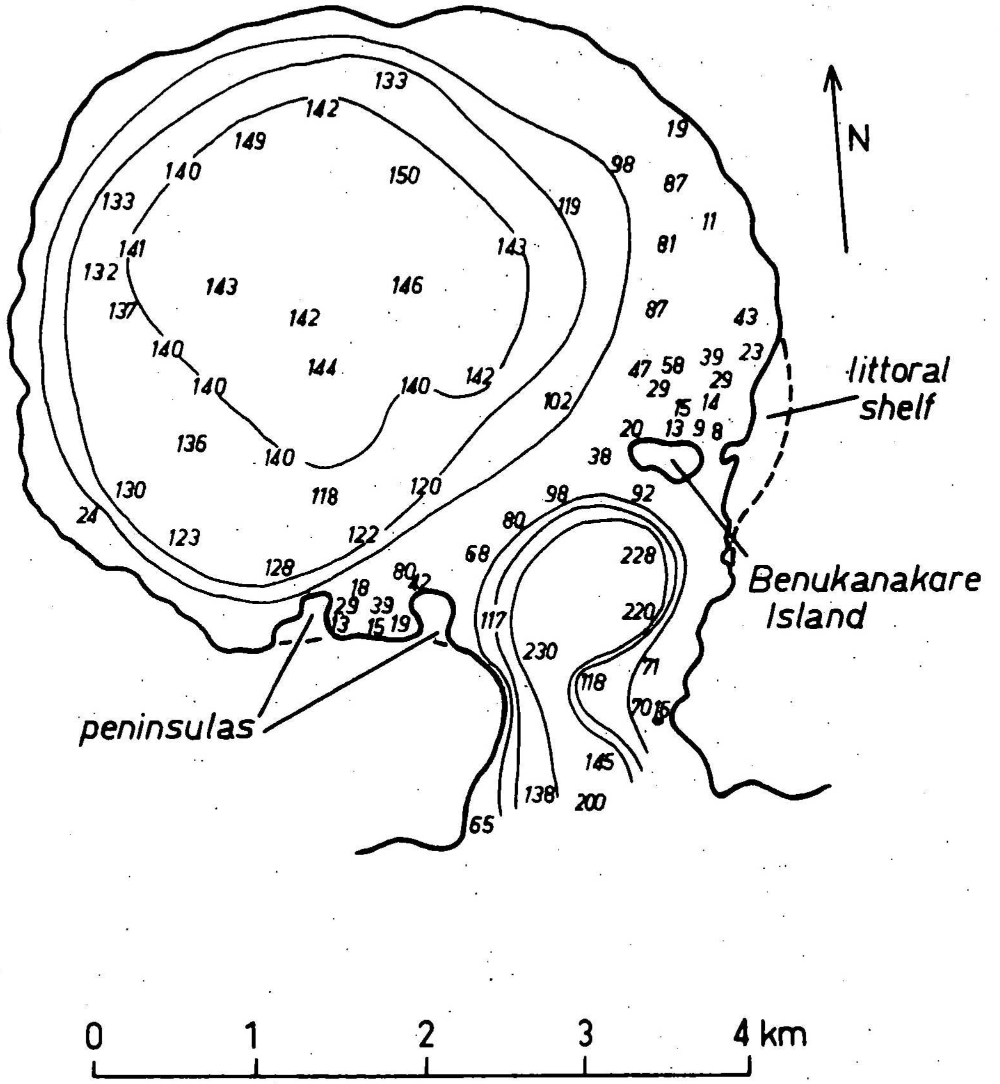
As both lava flows and clastic rocks make up the main volcano of the island, Garove is thought to be a stratovolcano. However, Garove shows features which are different from those of most other stratovolcanoes in the southern Bismarck Sea area. Firstly, the slopes of the outer flanks are uniform, and mostly less than 10^{o}. In contrast, stratovolcanoes such as Ulawun and Bamus, New Britain (Johnson, 1970a, 1971), have concave flanks that increase upwards to maximum slopes of more than 35^{o}. Secondly, perhaps because of the gentle slopes, many flows exposed in the caldera wall of Garove are over 15 m thick, whereas lava flows exposed on most stratovolcanoes in New Britain rarely exceed a few metres in thickness.

<u>The caldera and related features</u>

The Garove Island caldera is roughly circular (Fig. 28) and has a diameter of about 5 km, slightly smaller than the remnant caldera on Unea Island. The walls of the caldera are precipitous, and rise to between 100 and 150 m above sea-level; the highest point on the caldera rim, in the southeast, is about 350 m above sea-level.

According to the bathymetry on the German Admiralty chart, the floor of the caldera lies 140-150 m below sea-level (Fig. 33). The western wall of the caldera drops abruptly into water over 100 m deep, but in the east there is a gently sloping submarine shelf which extends southwestwards to form a submarine ridge just north of the entrance to Johann Albrecht Harbour.

Figure 33 Bathymetry of Johann Albrecht Harbour, Garove Island. Adapted from German Admiralty Chart (1909), showing 100, 120, and 140m depth contours. Depths in metres.



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The breach in the southern wall of the caldera is about 1 km wide, and bathymetry indicates that beneath the harbour entrance the sea reaches depths of over 200 m. The breach may have been caused either solely by marine erosion, or by collapse of part of the caldera rim, perhaps at the time of cauldron subsidence, and subsequent enlargement by marine erosion.

Two peninsulas in the southern part of the caldera, and Benukanakare Island in the east are formed of sub-horizontal lava flows (Figs 27, 28, 29 and 31); the mission has been built on the eastern peninsula. The peninsulas and island are a few tens of metres above sea-level and rise from the submarine ridge north of the harbour entrance. The two peninsulas descend gently northwards before ending in cliffs 12-15 m high, and both are formed of petrographically similar lava (samples 0025 and 0526 in Table 20). Marine shells are preserved on faces up to about 10 m above sea-level in cliffs surrounding both peninsulas indicating that both peninsulas may have been raised. Reynolds (1954a) first drew attention to the possibility of this uplift, and recorded stories by Garove Island villagers:

> '... unusual phenomena ... accompanied a change in sea level many years ago ... The inference of the stories was that the change was sudden and accompanied by increased emissions of steam from thermal zones. It was impossible to assess from natives interrogated how long this occurred, but palms estimated to be about 40 years old grow near the shore in the area to which the stories refer. This area embraces the Catholic Mission,

Balangori No. 2 village and Mt Utopi on the ridge south of the village and, according to the legend, most of the coastal portion to an height of about 300 feet was previously submerged.'

Benukanakare Island, off the eastern side of the caldera, is 10-12 m above sea level. East of the island a short stretch of coastline beneath the caldera wall forms a narrow shelf (Figs 25, 28 and 31).

These low flat-lying areas within the caldera, the submarine ridge from which they rise, and possibly part of the submarine shelf in the eastern part of the caldera, may all be parts of an arcuate segment of the cauldron block which did not sink as far as the main part of the caldera. Such a structure is preserved on the eastern side of the caldera on Long Island (Johnson, Taylor & Davies, 1972). The evidence for recent uplift of the two peninsulas in the south indicates that such an arcuate segment may be structurally unstable.

A second possibility is that the lavas forming the two peninsulas, Benukanakare Island, and the shelf are remnants of a series of post-caldera flows. This could explain the flat-lying attitude of the lava flows. However, as the bathymetry of Johann Albrecht Harbour shows no obvious submarine features which could be interpreted as post-caldera in origin, two periods of cauldron subsidence have to be postulated. After the first period, lava flows were ponded in the original caldera. A second period of cauldron collapse followed, during which most of the post-caldera rocks subsided to form the present caldera floor, but remnants of the post-caldera rocks were left as the two peninsulas, Benukanakare Island, and the littoral shelf.

Large scale uplift of Garove Island, implied in the story recorded by Reynolds (1954a), is considered unlikely, as no raised coral reefs, raised littoral deposits, or raised wave-cut platforms are present around the coast.

Satellite volcanoes

Satellitic volcanism has produced several minor cones and craters, now thickly vegetated, on the southwestern and northeastern outer flanks of Garove Island (Fig. 28).

In the southwest, a prominent cone formed of well-bedded ash and lapilli lies between Widu village and Langu. Part of the cone has been destroyed by the sea. The western remnant of another cone and its crater are preserved to the northeast, and two crescent-shaped breached cones lie north of Balangori No. 1 village. Further east, where the topography is rugged and irregular, arcuate cliffs may be remnants of crater walls. These cliffs have mantles of unconsolidated ash and lapilli and in a summit exposure bombs 1.5 m in diameter were seen, indicating a nearby vent.

Three satellite cones are preserved in the northeastern part of Garove Island. Two of the cones are symmetrical and have well-preserved summit craters. The third has been breached, and forms Peter Harbour. Lava and lapilli and oxidized scoriae crop out at various places around the shoreline of this harbour.

Thermal areas

Reynolds (1954a) described four thermal areas in the southern part of Garove Island. In Figure 28, these areas are labelled A, B, C, and D, following Reynolds designations. All four were located in 1970, and no others were found on the island.

Thermal area A is an emission of hot water below sea-level at the base of a cliff-forming lava flow. A temperature of 42°C was measured here, and a temperature of 48°C was recorded in a nearby beach.

Fumaroles are present in area B, on the track between Balangori No. 2 and Balangori No. 1 villages. Temperatures of 42 and 58°C were recorded, and no sulphuretted smell was detected.

Thermal area C is the most conspicuous of the four, and from a distance it appears as a light-coloured, bare area in the lower part of the eastern wall of the caldera. In 1970, conditions appeared to be the same as when observed by Reynolds in 1954. There were numerous fumaroles at the top of talus banks below an almost vertical cliff; the talus deposits were thermally altered, and sublimates, including sulphur, were widespread. Temperatures measured at points in the fumaroles and in altered talus deposits were 91, 101, 98, 79, 92, and 97°C.

Reynolds described thermal area D as '2 acres of hot ground', and on his map marked the area by two crosses. At this locality, visited by Davies in 1970, the extensive thermal area described by Reynolds was not found, and only a small area of stunted vegetation was located. Temperatures were below 30°C, and there was no sulphuretted smell or emissions of water vapour.

Petrology

Fifty-three rocks from Garove Island have been examined in thin section. Modal analyses of 20 samples, together with their locality descriptions, are given in Tables 20 and 21 respectively.

A feature of these rocks is their low total phenocryst content. Several samples are almost aphyric, containing less than

1 percent phenocrysts, and only two of the samples in Table 20 contain more than 20 percent phenocrysts.

Chemical analyses are available for two rocks from Garove Island. Sample 0538 is a low-silica andesite that contains 55.2 wt percent silica, and sample 0549 is a low-silica dacite containing 63.4 wt percent silica. Olivine is conspicuous in several rocks from Garove, and it is probable that basalts are present on the island.

Like the Unea rocks, zoned plagioclase is the most common phenocryst. Augite phenocrysts are more abundant than those of orthopyroxene but they rarely exceed a few percent of the rock. Orthopyroxene phenocrysts are absent in many rocks and in some samples are rimmed by augite.

Olivine phenocrysts are commonly present but never in amounts greater than 1 percent. In most samples they do not have coronas of pyroxene or iron-titanium oxides.

Iron-titanium oxide phenocrysts are commonly present but rarely exceed 1 percent. A few samples, for example 0538, contain sparse aggregates of iron-titanium oxides and pyroxene which may be pseudomorphing amphibole, but no primary amphibole has been recognized. Several samples contain small phenocrysts of apatite.

The groundmass of most Garove Island samples is very fine-grained or glassy. A few rocks are pitchstones, composed of glass studded with microlites, but most have crystalline groundmass in which plagioclase, iron-titanium oxides, and augite are the most easily recognized minerals. Groundmass orthopyroxene is present in less fine-grained rocks, and low-2V clinopyroxene has been identified in some samples, for example 0559. Olivine is also present in the groundmass of some samples, and is especially abundant in sample 0572, which contains no orthopyroxene.

Interstitial cristobalite is present in samples 0026 and 0559, and well-developed crystals of tridymite are found in vesicles in samples 0025, 0534, and 0550. Both minerals also occur in other samples.

TABLE 20. MODAL ANALYSES OF 20 ROCKS FROM GAROVE ISLAND

Group	Sample number (prefix 48NG)	Volume % phenocrysts					Total % phenocrysts
		Plagioclase	Olivine	Ortho-pyroxene	Augite	Fe-Ti Oxides	
1.	0028	8	-	<1	1	<1	9
	0559(a)	74	<1	total pyroxenes = 21 (augite > orthopyr.)		3	
	0025	17	-	1	3	1	22
	0526	16	<1	1	3	2	22
	0532	14	-	<1	1	<1	15
	0534	10	-	<1	1	<1	11
	0537(b)	<1	-	-	<1	-	ca.1
	0538(b)	<1	-	-	<1	<1	ca.1
	0542	<1	<1	-	<1	-	ca.1
	0546	9	<1	-	1	-	10
	0547	<1	<1	-	<1	-	ca.1
	0549	9	-	1	1	<1	11
2.	0556	<1	<1	-	<1	<1	ca.1
	0572(c)	<1	<1	-	-	-	1
	0575	3	-	-	<1	-	3
3.	0034	3	-	<1	1	<1	4
	0035	<1	-	-	<1	<1	ca.1
	0031	3	<1	-	1	<1	4
	0033	5	1	<1	1	<1	7
	0036	7	<1	-	3	-	10

(a) coarse-grained sample in which all mineral grains have been counted, except for 2 percent indeterminate fine-grained materials.

(b) sample contains fine-grained pseudomorphs (<1%) which may be after amphibole.

(c) sample has a coarse-grained groundmass in which many ferromagnesian grains could be considered as microphenocrysts.

TABLE 21. LOCALITY INDEX FOR SAMPLES OF TABLE 20, AND FOR THOSE REFERRED TO IN TEXT

Group	Sample	Locality description
1. Caldera wall of Johann Albrecht Harbour	0028	in situ lava on spur, western side of harbour entrance
	0559	xenolith in in situ lava, western side of harbour entrance
	0025	block from east side of mission peninsula
	0024	in situ lava flow, west side of mission peninsula
	0526	in situ columnar-jointed lava flow
	0532	in situ lava flow, over 12 m thick
	0534	block derived from lava flow in cliff above shoreline
	0537	vertical dyke exposed at shore
	0538) 0542)	block derived from cliffs above shoreline
	0546	in situ lava flow, crudely jointed
	0547	in situ sample from same flow as 0546
	0549	in situ lava flow forming Benukanakare Island
	0550	block from in situ volcanic rudite
	0026	talus block just north of thermal area C
2. Coast east of harbour entrance	0556	in situ lava flow, 8 m thick
	0572	block from in situ volcanic rudite
	0575	in situ lava outcrop, crudely jointed
3. Coast west of harbour entrance	0034	in situ lava outcrop
	0035	in situ lava outcrop
	0031	in situ aa lava flow, headland near Balangori No. 1 village
	0033	in situ lava flow near Langu plantation house
	0036	in situ lava flow, west coast

MUNDUA AND ASSOCIATED ISLANDS

A cluster of small volcanic cones form Mundua Island and the nearby smaller islands to the west (Fig. 23). These volcanoes are much smaller than the main volcano of Garove Island.

Mundua and Wingoru Islands

Mundua Island and Wingoru Island to the west are formed of a series of coalescing basaltic volcanoes along a linear zone about 7 km long and slightly more than 1 km wide which trends a few degrees south of due west (Fig. 34). This zone cuts across the general trend of the Witu zone, between Ottilien Reefs and Garove Island, at about 15°.

There are three principal villages on Mundua Island and one on Wingoru Island. Much of the central part of Mundua is covered by Wingau Plantation. Both islands are vegetated and undissected, and both are surrounded by coral reefs.

The largest volcanic centre forms Wingoru Island and the western end of Mundua Island. Remnants of a crater wall are preserved in the east and west separated by narrow sea-filled channels. East of this remnant crater is the highest point on Mundua Island, 152 m above sea-level (Lae Sheet). The peak is the summit of a craterless volcanic cone which extends across the entire width of Murdua Island. A small thermal area was reported at the top of the cone by local villagers in 1970, and a slightly warm spring was observed on the coast a few hundred metres west of Karramatta village.

The central and eastern part of Mundua Island consists of a low ridge on which five small cones have been built. Two of these cones, south and southeast of Korei village, have well-defined

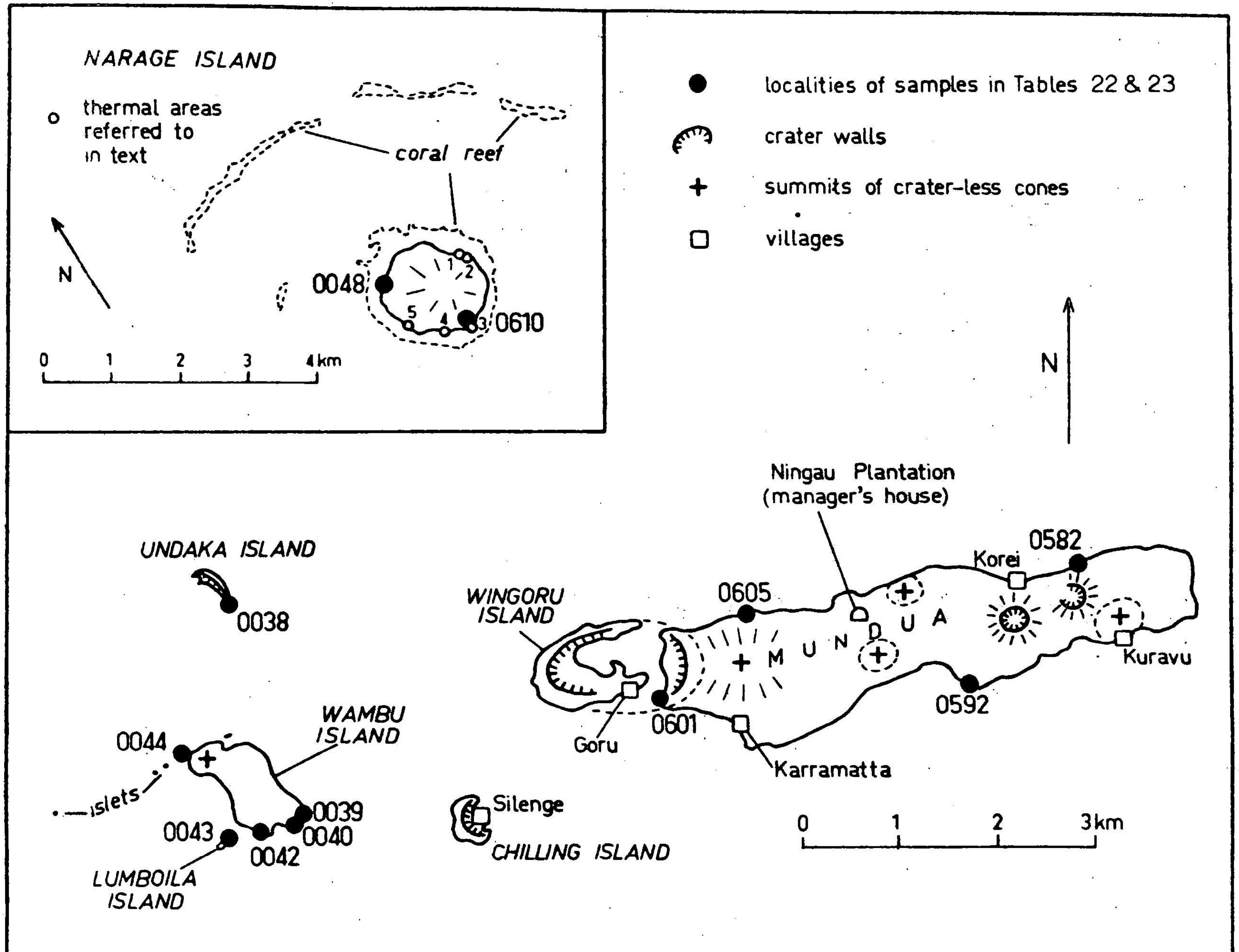

Figure 34 Mundua, Wingoru, Chilling, Wambu, Lumboila, Undaka, and Narage Islands. Adapted from German Admiralty chart (1909) and aerial photographs taken 6/7/66.

To accompany Record 1972/133

circular craters about 300 m in diameter, but the other three have no craters.

The rocks exposed around the coast are mostly well-bedded clastic deposits of ash, lapilli, and scoriae, and they indicate that the history of these islands was probably dominated by explosive eruptions. There are also exposures of basaltic lava flows and dykes; one dyke, due south of the manager's house at Ningau Plantation, is about 6 m wide.

On the headland southeast of Karamatta village, 10 m of bedded ash and scoriaceous lava clasts dip northwestwards at 18°. These deposits may represent a remnant of another eruptive centre.

Wambu, Lumboila, Chilling, and Undaka Islands

These four islands lie west of Mundua and Wingoru (Fig. 34), and are remnants of volcanoes whose eruptions were almost exclusively explosive. Coral reefs fringe the islands and form an extensive complex west of Wambu Island (Fig. 25).

Wambu (or Vambu), the largest of the four islands, has exposures of seaward-dipping clastic deposits around most of its shoreline, indicating that there is probably an eruptive centre in the middle of the island, although no crater is preserved there. The deposits are arenaceous and rudaceous, and are composed predominantly of light brown to buff vesicular fragments, but they also contain sproadic angular blocks of poorly vesicular lava. The light brown to buff colour is probably due to sideromelane and palagonite, which are thought to be common constituents of the deposits. On the southeastern end of the island, at sample points 0039 and 0040, the clastic deposits are cut by two irregular sheets of vesicular lava, each about 30 cm wide.

At the northwestern end of Wambu Island an oxidized, scoriaceous lava flow is overlain by a pyroclastic cone. This flow also crops out on a nearby islet. Lumboila Island, an islet less than 100 m long off the southwest coast of Wambu, consists of a near vertical northeast trending dyke, flanked by scoriaceous lava, scoriae, and lapilli beds. This dyke also crops out on the southwest shore of Wambu Island.

Chilling Island is the remnant of a volcanic cone, the eastern part of which was presumably destroyed by the sea. The island is made up of bedded volcanic arenaceous and rudaceous deposits similar to those on Wambu Island.

Undaka Island is the elongate remnant of a much larger volcano. The southwest side is part of a comparatively steep crater wall, and the northeastern side represents part of the original flanks. Clastic deposits similar to those on Wambu and Chilling Islands are exposed on the southwestern side. Thin section examination of one sample of arenaceous material from Undaka shows fragments of sideromelane, partly altered to palagonite.

The presence of sideromelane and palagonite indicates that during eruption the magma probably came into contact with water.

Petrology

Twenty one samples from these islands have been examined in thin section. All are characterized by the presence of olivine phenocrysts and absence of orthopyroxene phenocrysts, suggesting they are mainly, if not entirely, of basaltic composition. Sample 0042, from Wambu Island, is a basalt having a silica content of 48.6 wt percent. Modal analyses of ten samples are given in Table 22 (groups 1 to 4). Most samples have total-phenocryst contents of less than 20 percent.

Zoned plagioclase phenocrysts are common in most rocks, but in many are less abundant than olivine phenocrysts. In sample 0048A, an unusual feature is the presence of a plagioclase phenocryst rimmed by augite grains.

All the samples in Table 22 contain at least 1 percent olivine phenocrysts, and in five samples olivine is the only phenocryst forming one or more percent of the total rock. Many olivine phenocrysts are euhedral, and none have coronas of pyroxene. However, in samples 0582 and 0043 olivine phenocrysts are rimmed and in some cases completely pseudomorphed by iron-titanium oxides.

Augite phenocrysts are present only in rocks from Mundua and Wingoru Islands, and orthopyroxene phenocrysts have not been recognized in any of the twenty one samples. Iron-titanium oxide phenocrysts are present in a few rocks only, and in none do they exceed 1 percent.

In the groundmass, plagioclase, augite and iron-titanium oxides are by far the most abundant minerals. Olivine is a common constituent, and in several samples, low-2V clinopyroxene has also been identified, but appears to be much less abundant than augite. Some grains of iron-titanium oxides have lath-like habits, and may be ilmenite.

<u>NARAGE ISLAND</u>

Narage (or Narrage, North, or Gipps) Island overlies the deepest part of the New Britain Benioff Zone, and is further from the New Britain submarine trench than any of the other Witu Islands' volcanoes (Fig. 33).

Narage is a steep-sided central volcano which has a radial pattern of incised streams (inset of Fig. 32). According to the Lae Sheet, the summit of the island is 315 m above sea-level. Narage is uninhabited and thickly vegetated. Numerous thermal areas occur around the coast. The island has a fringing reef and also an offshore barrier reef 2-3 km off the western and northern coasts.

At the summit of the volcano there are two peaks (Fig. 32) which may be remnants of a summit crater. The summit is slightly southeast of the centre of the island, and on the long northwestern flank there is a prominent break in slope almost half way up the volcano.

Lava flows crop out where spurs reach the shoreline, and clastic deposits are exposed elsewhere around the coast. At sample locality 0048 lava flows about 0.5 m thick are interlayed with scoriae, indicating that Narage is a stratovolcano. The lavas are probably basalts.

Fisher (1957) described 'boiling springs' on the southeastern and southwestern sides of Narage Island. In 1970, numerous thermal areas were found around the coast, five of which are numbered in Figure 34, and a more detailed survey of the island would probably establish several more thermal points along the shoreline.

At (1) in Figure 34, hot waters bubble from beach sands, and sand and water near boiling point are ejected to heights of 60-70 cm. The most extensive thermal area is at (2), beneath a grass-covered spur, where boiling water is thrown out of cavities between boulders of altered rock and areas of sublimates and oxidised soil and mud.

Maximum temperatures of a little less than 100°C were measured here. Smaller, but prominent, bubbling springs of hot water were also located at points (3), (4) and (5).

Petrology

Five samples from Narage Island have been examined in thin section, and two modal analyses are given in Table 22 (group 5). Phenocrysts of olivine, but not orthopyroxene, are present in all five samples which are probably basalts similar in chemical composition to those from Mundua, Wambu, Lumboila, and Undaka Islands. The Narage rocks are similar to the other rocks shown in Table 22 except that they have much higher phenocryst contents.

TABLE 22. MODAL ANALYSES OF 12 ROCKS FROM MUNDUA, WAMBU, LUMBOILA, UNDAKA, AND NARAGE ISLANDS

Group	Sample Number (prefix 48NG)	Volume % phenocrysts					Total % Phenocrysts
		Plagioclase	Olivine	Ortho-pyroxene	Augite	Fe-Ti oxides	
1.	0582	-	10	-	-	-	10
	0592	13	7	-	2	<1(a)	22
	0601	6	1	-	<1	-	7
	0605	14	1	-	8	-	23
2.	0039A	<1	1	-	-	-	1
	0040	<1	9	-	-	-	9
	0042	7	4	-	-	<1(b)	11
	0044	-	9	-	-	<1	9
3.	0043	6	10	-	-	-	16
4.	0038A	<1	7	-	-	-	7
5.	0048A	40	3	-	4	<1	47
	0610	25	4	-	10	<1	39

(a) small, rare, microphenocrysts

(b) one prominent grain only

TABLE 23. LOCALITY INDEX FOR SAMPLES OF TABLE 22.

Group	Sample	Locality description
1. Mundua Island	0582	in situ lava flow, north coast
	0592	in situ lava flow, south coast
	0601	in situ lava flow, southwestern tip of island
	0605	in situ lava flow, north coast
2. Wambu Island	0039A	lava vein cutting clastic deposits, southeastern coast
	0040	another lava vein cutting clastic deposits, southeastern coast
	0042	in situ lava flow, southwestern coast
	0044	in situ lava flow, islet off northwestern coast
3. Lumboila Island	0043	dyke forming central ridge of island
4. Undaka Island	0038A	lava fragment in clastic deposits
5. Narage Island	0048A	in situ lava flow, east coast
	0610	in situ lava flow, southeastern coast

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