DEPARTMENT OF
MINERALS AND ENERGY

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

Record 1973/89

QUATERNARY VOLCANOES OF THE CENTRAL AND SOUTHERN HIGHLANDS OF PAPUA NEW GUINEA

by

D.E. Mackenzie

Record 1973/89

QUATERNARY VOLCANOES OF THE CENTRAL AND SOUTHERN HIGHLANDS OF PAPUA NEW GUINEA

by

D.E. Mackenzie

CONTENTS

SUMMARY

The Quaternary volcanoes Mount Hagen, Mount Ialibu, Doma Peaks, Mount Ne, Mount Bosavi, Mount Murray, Mount Duau, Mount Favenc, Aird Hills, and Mount Yelia in the Highlands of Papua New Guinea were visited during September-November 1971. Mount Hagen was studied in detail, Mount Murray, Doma Peaks, and Mount Yelia in somewhat less detail, and the others were reconnoitred.

All the volcanoes are made up of intercalated lava flows, pyroclastics, lahars, agglomerate, and outwash; the proportions of lava flows and agglomerate decrease markedly away from each eruptive centre.

Mount Hagen is a composite of three stratovolcanoes, the southern part containing collapse calderas. The bulk of the complex is made up of highly porphyritic shoshonite (or high-potash olivine basalt), with a younger, caldera-filling high-potash andesite-dacite complex in the southernmost centre.

Mount Ialibu is a highly dissected stratovolcano cut on its northern flank by a major fault, and in the summit area by several smaller faults. It is made up largely of pyroxene andesite with prominent plagioclase phenocrysts, and minor amounts of olivine basalt and hornblende-bearing andesite.

Doma Peaks is a structurally complex volcano made up of at least three superposed successively younger and smaller eruptive centres. The lavas are largely pyroxene andesite with lesser olivine-bearing andesite and basalt, and minor hornblende pyroxene andesite. There are several cold but active solfataric areas and gas seeps.

Mount Ne is the severely eroded stump of a pyroxene andesitic volcano, similar to parts of Doma Peaks.

Mount Kerewa is a deeply dissected stratovolcano with a large eroded crater area which lacks a western wall. It is made up largely of two-pyroxene andesite, with very minor olivine-bearing andesite and olivine basalt.

Mount Bosavi is a deeply eroded central-type stratovolcano with a crater greatly enlarged by erosion, and a very extensive apron containing abundant outwash deposits. The lavas are highly porphyritic shoshonite and less common hornblende-pyroxene andesite. The andesite appears to overlie the shoshonite.

Mount Murray is also a central stratovolcano, even more severely eroded than Mount Bosavi, and has 'basement' limestone exposed in the crater floor area. The lavas are mainly weakly porphyritic, silica-saturated shoshonite, with minor hornblende-pyroxene andesite, largely as dykes in the crater area. Rocks in the crater area are commonly altered or metamorphosed, and some andesite dykes are rich in pyrite.

Mounts Duau and Favenc are very deeply eroded, and underlying sedimentary rocks are exposed in gorges close to their crater areas. Mount Duau is composite, with a small cone filling the eroded crater or caldera

of an older centre. These centres are made up of porphyritic shoshonite, olivine-two-pryoxene and two-pyroxene basalt, and hornblende-pyroxene andesite. The major rock types, shoshonite and andesite, are represented in about equal proportions.

Aird Hills is a ring-like group of moderately dissected rounded hills which resemble cumulodomes. They are composed of highly porphyritic hornblende-bearing andesite and dacite, which are characterized by euhedral plagioclase phenocrysts up to 1.5 cm long.

Mount Yelia consists of a main cone with its crater largely filled by a later dome complex, and a group of domes low on the northern flank. There are several cold solfataras in the main crater area. The lavas are largely hornblende-pyroxene andesite, with minor dacite and potassium-rich olivine-bearing basalts. Marble Peak is an eroded arcuate volcanic escarpment facing west, with the remnants of a possible caldera at its base. A specimen of shoshonite was collected from the summit.

Dates on the volcanic rocks range from 800 000 years for lavas probably related to Mount Kerewa to 200 000 years for andesites from Mount Hagen. Pyroclastic deposits in lake sediments near and traceable to Mount Hagen have been dated at 25 000 - 30 000 years; others are as young as 190 years, but are of unknown origin. There are legends of major eruptions at Doma Peaks, and Mount Yelia must have been active in the last few hundred, or even tens of years.

The petrographic data suggest that the andesites in the Highlands volcanoes were derived from a parental shoshonitic magma by crystal fractionation. This may have taken place in magma chambers between 1 and 5 kilometres beneath each volcano. The parental magma is thought to originate from the mantle, possibly from sinking quartz ecologite, and may have been enriched in potassium and other light elements by zone refining in the low velocity zone.

Some of the large crater and caldera structures are thought to be due to a trap-door-like collapse phenomenon, whereas in others a contributing factor may be preferential erosion caused by orographic rainfall on the windward side.

There is a suggestion of a link between Highlands-type high-potash basaltic and andesitic volcanism and porphyry copper mineralization such as at Ok Tedi (Mt Fubilan).

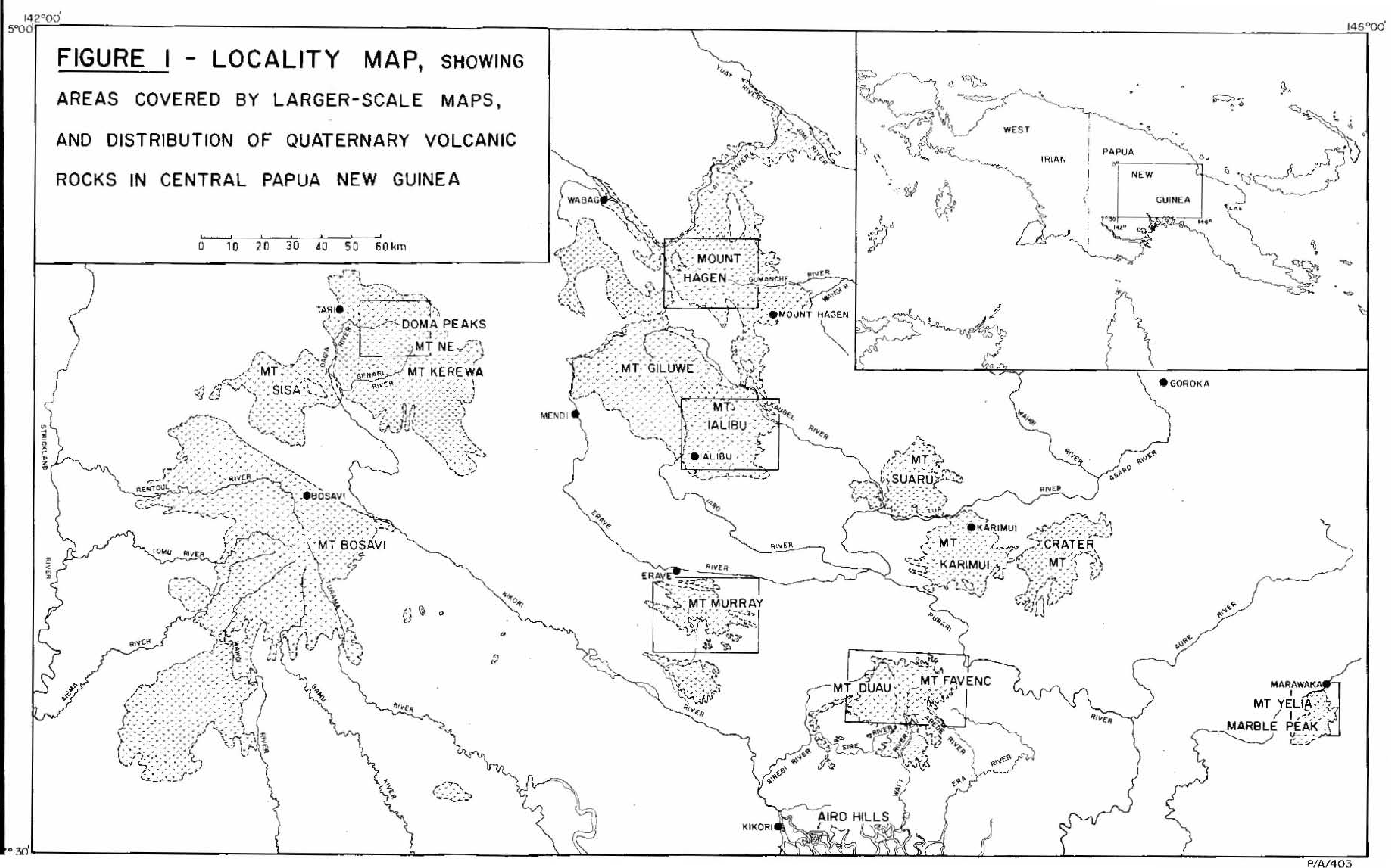


FIGURE 1 - LOCALITY MAP, SHOWING AREAS COVERED BY LARGER-SCALE MAPS, AND DISTRIBUTION OF QUATERNARY VOLCANIC ROCKS IN CENTRAL PAPUA NEW GUINEA

INTRODUCTION

During the regional geological mapping of the Kubor Range area (Bain, Mackenzie & Ryburn, 1970) and the Baiyer River - Jimi Valley area (Mackenzie & Bain, 1972), specimens were collected from the Quaternary volcanoes Mount Hagen (or Hagen Range), Mount Giluwe, Mount Ialibu, Mount Suaru, Mount Karimu, and Crater Mountain. Laboratory studies showed these specimens to belong to the shoshonitic and high-K calc-alkaline associations (Mackenzie & Chappell, 1972), and aroused considerable interest in the volcanoes. A party consisting of the author and Dr R.W. Johnson, assisted for part of the time by Messrs I.P. Sweet, D.S. Hutchison and R.J.S. Cooke, visited all the other major Quaternary volcanic centres in the region, except Mount Sisa, during the period 19 September to 22 November, 1971. These centres included Mount Yelia (R.W.J.)*, Mount Ialibu (R.W.J.), Doma Peaks (R.W.J., D.S.H., I.P.S., D.E.M., R.J.S.C), Mount Ne (R.W.J.), Mount Kerewa (R.W.J., I.P.S), Mount Bosavi (R.W.J., I.P.S., D.S.H), Mount Murray (D.E.M), Mount Duau (R.W.J., I.P.S), Mount Favenc (R.W.J., I.P.S), and Aird Hills (R.W.J., I.P.S) (Fig. 1). Some additional detailed work was done on Mount Hagen (D.E.M).

A four-wheel-drive vehicle was used for the work on Mount Ialibu and for some of the work on Mount Hagen. The remainder of the work was conducted with the aid of a Bell 47G3B1 helicopter from suitable bases near the volcanoes. Light aircraft were used to transport personnel and equipment from one base to another, so each base was at or near a C class airstrip (Fig. 1).

Base	Volcano/Volcanoes
Mount Hagen	Mount Hagen
Marawaka	Mount Yelia
Ialibu	Mount Ialibu
Tigibi Mission, near Tari	Doma Peaks, Mount Ne, Mount Kerewa
Bosavi Mission	Mount Bosavi
Erave	Mounts Murray, Duau and Favenc, and Aird Hills

Previous work

Noakes (1939, unpubl. rep.) first reported the volcanic nature of Mounts Hagen, Giluwe, and Ialibu, and Rickwood (1955) briefly described them. The Australasian Petroleum Company (1961) described Mounts Bosavi, Biwau[1] Rentoul (Sisa), Lema[2], Ma'a[2], Iane[2], Kase[2], Duau, Favenc and Murray, and Aird Hills; theirs was the first reporting of these centres and includes all volcanic centres in the area surveyed by the company. Branch (1967) visited Mount Yelia, and Morgan (1963, 1966) analysed specimens from the volcano collected earlier by non-geologists. Jakeš & White (1969)

---

* Initials indicate geologist(s) who visited each volcanic centre.

1. Minor centre not examined during the 1971 survey.

2. Minor centres along the Darai Hills; not examined.

published eight analyses of rocks from Mounts Hagen, Giluwe, and Ialibu, and recognized their shoshonitic characteristics. Field work in 1968 by Bain et al. (1970) resulted in discussions of the Quaternary volcanoes in the Highlands by Mackenzie (1970), Johnson et al. (1971), and Johnson et al. (1972). Taylor (1971) visited Doma Peaks in 1968 and reported on the solfataric and hydrothermal activity.

Landforms, soils, and glacial features of some of the Highlands volcanoes have been discussed by Perry et al. (1965), Bik (1967), Rutherford (1968), Löffler (1971), and Blake & Löffler (1971). These authors were concerned mainly with Mounts Giluwe, Hagen, and Ialibu.

MOUNT HAGEN

MORPHOLOGY

Viewed from Mount Hagen town, the Hagen Range is a broad, almost flat-topped range with slightly concave to slightly convex slopes of 15° to 20° at either end (Fig. 3), rising some 2100 m above the surrounding plains. The profile is broken by several small irregularities in the grassy southern summit area, and by a deep V-shaped notch near the northern end. This notch marks the junction of a northern cone and a caldera to the south, as described below, and is occupied by Ambudl Creek (Wara Ambudl). The profile from the south (Fig. 4) is a shortened version of that described above. From the north the profile consists of a smooth convex eastern slope sharply truncated near the crest by the deep gorges of the western side.

Mount Hagen, or Hagen Range, volcanic complex is elliptical in plan, and made up of three coalesced cones aligned north-northeast (Fig. 2). The southern and central cones overlap so that their eastern slopes merge almost imperceptibly into one another, with only a slight irregularity in the smooth curvature in plan. The northern cone is partly separated from the central one by a cuspate notch which has been enlarged into a deep V-shaped gorge (Fig. 3); its summit was probably originally separately from that of the central cone.

The central and southern cones have small, intersecting summit calderas; the southern caldera is partly filled by a central andesitic complex now eroded to a series of craggy ridges (Fig. 8). Also in the southern caldera, at the head of the Anji River, there are two prominent, very steep-sided hills (Fig. 8): these represent volcanic plugs. Two similar, though smaller and more rounded hills occur in a flat area partly encircled by arcuate ridges near the upper reaches of the Laneme River, in the central caldera. These features probably represent plugs surrounded by a small relict caldera rim, or the eroded stump of a small volcano. The northern cone has at least two summit craters, but its form is partly obscured by the deep, possibly fault-controlled valley which truncates its western side.

There is a steep-sided, almost flat-topped 600 m-high cone on the southeastern flank of the southern centre (Fig. 5), and a small, rounded 100-150 m-high satellite cone high on the northeastern flank of the northern centre.

TABLE I - GENERAL REFERENCE FOR MAPS

GEOLOGICAL SYMBOLS

GEOLOGICAL BOUNDARY

FAULT

ANTICLINE (with plunge)

SYNCLINE (with plunge)

MONOCLINE

ATTITUDE OF BEDDING

• 1504 SPECIMEN/OBSERVATION LOCALITY

VOLCANIC FEATURES

VOLCANIC OR ERODED VOLCANIC ESCARPMENT

CRATER

SATELLITE CONE

DOME

PIT CRATER

DEPRESSION

EDGE OF LAVA FLOW

SUBVOLCANIC INTRUSION

EDGE OF PLANEZE

EROSIONAL ESCARPMENT

LITHOLOGICAL SYMBOLS

Qa	ALLUVIUM
Qs	LAKE SEDIMENTS
Qpg	GILUWE VOLCANICS
Qph	HAGEN VOLCANICS
Qpi	IALIBU VOLCANICS
T-Qs	CLASTIC SEDIMENTS
Ts	SEDIMENTS (incl. limestone)
M-Czs	MESOZOIC and CAINOZOIC SEDIMENTS (mainly Cretaceous)
M	MESOZOIC SEDIMENTS (largely Cretaceous)

CULTURAL FEATURES

ROADS

TOWN; VILLAGE

AIRSTRIP

MISSION

FIGURE 2 - GEOLOGY OF THE HAGEN VOLCANIC COMPLEX

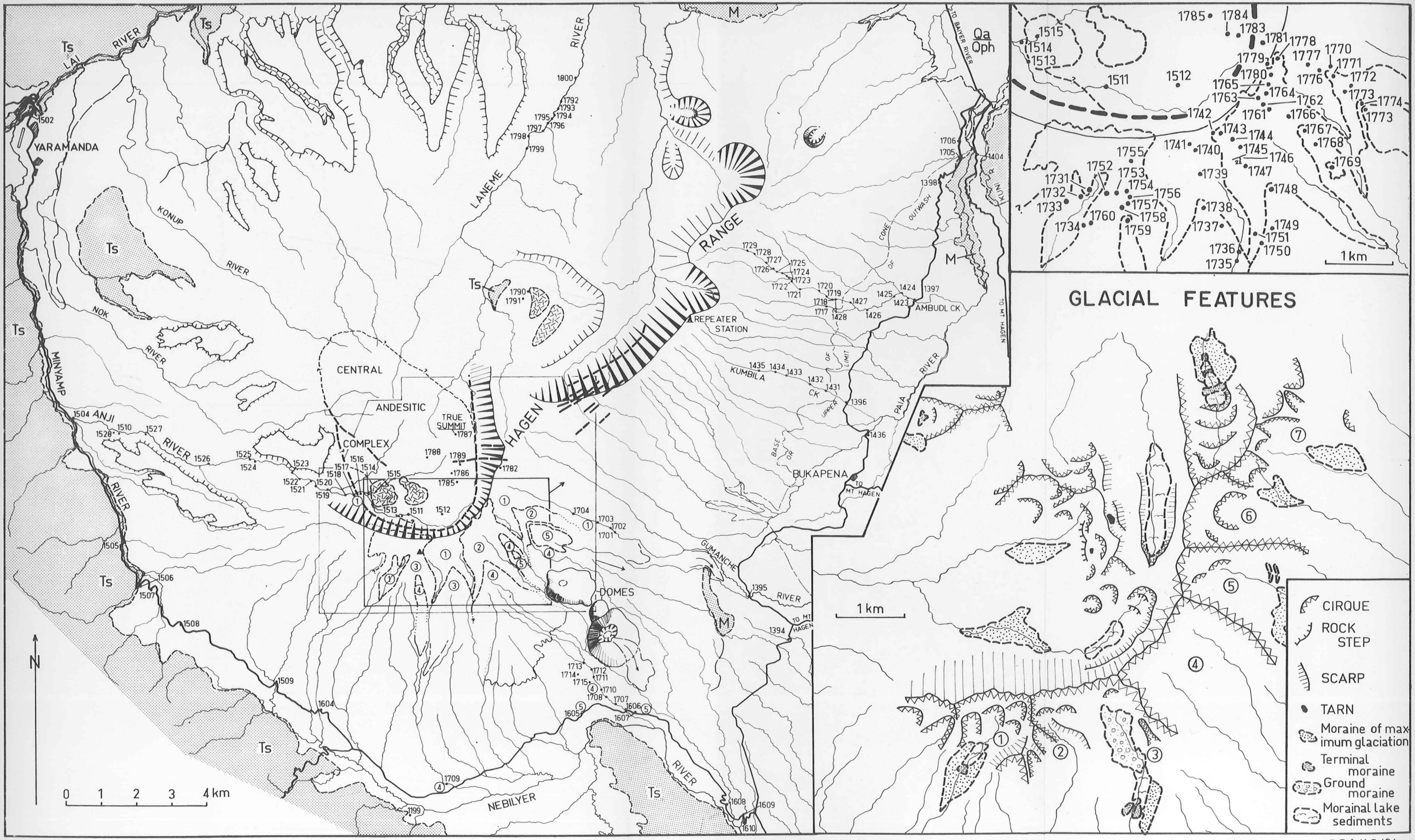


Figure 3. Profile of the Hagen Range from the southeast, at Mount Hagen's Kagamuga airport. The grass-covered southern summit area, and the deep notch separating the northernmost cone from the central caldera complex are clearly visible. The airport is built on flat-lying pyroclastics, outwash and lahar deposits from the Hagen volcanic complex. Negs. GA/4552,4556.

Figure 4. Mount Hagen from the south, at Tomba sawmill. The deeply gorged upper slopes and craggy summit area are well shown. Lava flows dip at about 25° southeast at centre, and at an apparent 5° at right, on the summit area. Neg. GA/5434.

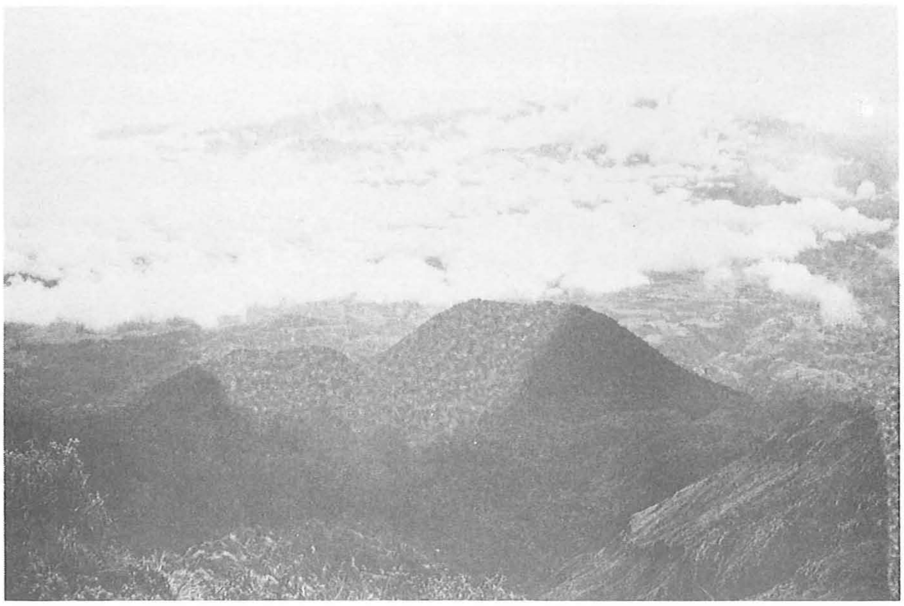


Figure 5. Satellite cone and dome on the southeast flank of Mount Hagen. Lava flows exposed in the right foreground are on the ridge between valleys 3 and 4. In the distance is the cloud-shrouded Kubor Range. Neg. GA/5418.

The heavily forested southern and eastern slopes of the complex are well preserved constructional surfaces cut by deep, steep-sided stream valleys. These valleys vary in size with the size of the stream, and become deep and more V-shaped headwards (Fig. 4). Several of the larger streams originate in broad valleys of glacial origin in the summit area. Deep erosion has obliterated almost all the original constructional surfaces on the western and northern sides of the complex, so that the caldera rims are missing on these sides. This may have been caused by initial asymmetry of the volcano, and by higher precipitation on the northwest side. Only a few small planezes remain on high forested spurs between deep steep-walled valleys. These valleys are up to 1200 m deep, and their walls, some close to vertical, are heavily scarred by rockfalls and landslides. After heavy rain, waterfalls up to almost 900 m high are a common sight.

Glacial features in the summit area (Fig. 2) (see also Perry et al. (1965) and Löffler (1971).)

The rims of the southern and central calderas and the crags of the central complex rise to over 3500 m, the highest point being one of the central peaks at around 3800 m. (The survey marker, near the southern caldera rim, is at 3762 m above sea level.) Thus a large area of the summit region of the Hagen Range is above the late Pleistocene and early Holocene snowlines, which descended as low as 3500 m above sea level. The caldera rims and upper cone slopes are sculptured into a series of broad, spoon-shaped valleys with moderately steep craggy headwalls (cirques) and separated by smooth to moderately serrated knife-edge ridges. Small cirques can be recognized in some of the headwalls and ridges. The valleys become broader and shallower to the north and finally give way to flat grassy plains dotted with small ponds at the central caldera rim decreases in height. In Figure 2 the valleys have been numbered consecutively from southwest to northeast, or anticlockwise.

The floor of valley 1 is flat and swampy, and underlain by laminated lacustrine shales over coarser glacial deposits. Lateral moraines extend downslope from the ridges bounding the west and east sides, and a small hummocky terminal moraine blocks the lower end of the valley. The stream which drains this valley has cut a small gorge through the terminal moraine, exposing angular, unsorted debris whose largest fragments are almost a metre across.

Valley number 2 is a composite of several cirques, and is partly covered by hummocky moraine. Valley 3 (Fig. 6) is the best developed and preserved of the glacial valleys, though the headwall shows few distinctive features. The upper part of its floor is covered by hummocky moraine and slump deposits, while the lower part is flat and swampy, with underlying lacustrine deposits, as in valley 1.

There is a small terminal moraine bisected by a stream at the bottom of the valley. The stream has exposed varved shales containing wood fragments and a few large angular erratic blocks, and unsorted coarse morainic detritus, overlying fresh jointed lava. A lateral moraine extends from the end of the ridge on the eastern side of the valley.

Valleys 4 and 5 have few distinctive features apart from a few small cirques, hummocky floors, and several small ponds on flat benches. Terminal or lateral moraines or both occur at the bottoms of valley 7 and the small valley between valleys 7 and 6.

Glacial features of the inner complex and the inside of the caldera rims are more complex. A deep, curved, and elongated glacial valley at the head of the Anji River separates the southern caldera rim from the central complex (Fig. 7). Two small cirques form steps at the head of the valley, and part of its floor is covered by flat-lying lacustrine deposits. An extensive moraine of maximum glaciation extends from the end of the spur on the north side of the valley. The highest parts of the central complex are deeply scarred by many small to moderately large cirques, but little morainic debris remains. There are a number of tarns in this area, situated on flat areas between ridges, or on cirque floors; the largest of these, close to the true summit of the range, is about 115 m long, 60 m wide, and up to 6 m deep. Immediately to the east of this lake, between the central complex and the eastern wall of the southern caldera, is a 500 m-deep elongated glacial valley, whose floor is covered by extensive lacustrine and patchy moraine deposits.

A large, gently undulating area of short grass and patches of stunted forest occurs between the eastern rims of the southern and central calderas. Valleys 6 and 7 are on its eastern side, and on its western side is a broad, shallow spoon-shaped valley, and to the north, two smaller, deeper cirques. The floor of the larger valley is divided into a series of steps by six low, arcuate scarps, and there is a small but prominent lateral moraine extending from the end of the eastern ridge.

GEOLOGY

Lower slopes and apron

The very extensive apron and the lower slopes of the Hagen complex consist of basaltic and rare andesitic lavas, lahar deposits, ash, tuff, and derived fluviatile sedimentary detritus of all size grades. The lava flows range from a few tens of centimetres to several tens of metres thick; and have a thin vesicular and partly brecciated base, a massive core, and a thick vesicular and brecciated upper zone. The fronts of flows are a mass of jumbled blocks and fine ash and other material. The proportion of flows in the deposits of the lower slopes and apron decreases away from the eruptive centre, and lahars, ash tuff, and sediments become predominant. Sequences of lahars made up of large angular blocks of lava in a sandy to muddy matrix, overlain by banded or laminated ash and tuff of coarse grit to fine sand size, are common in road cuttings. Further information is presented by Mackenzie & Bain (1972).

Middle slopes and western gorges

Basaltic and scarce andesitic flows dominate the well preserved middle slopes on the southern and eastern sides of the complex. The flows are a few tens of centimetres to about 30 m thick, and generally have smooth, in places vesicular bases, and vesicular, commonly brecciated tops. They

Figure 6. Number 3 valley, summit area of Mount Hagen, looking south. In the immediate foreground are outcrops of shoshonite. Below are hummocky ground moraines, with scattered tarns. At the end of the valley are flat-lying lake sediments and a high morainal ridge (largely grassy). Neg. GA/5421.

Figure 7. Southern crater wall and internal glacial valley, Mount Hagen, from the northeast. Numerous lava flows are exposed in the upper part of the scarp. The small vertical scarp halfway up the 450 m-high main wall is probably a collapse fault. Neg. GA/5414.

are intercalated with weathered ash and rubble beds, some weathered agglomerate, and rare sedimentary beds - particularly volcanic rudite, with angular to subrounded fragments - which become more common down the slopes. Hornblende-bearing flows are rare on the eastern slopes, whereas there are several hornblende-bearing andesitic flows and a few hornblende-bearing basaltic flows on the southern and southeastern slopes. The hornblende-bearing flows are at and near the top of the volcanic pile, and in places can be seen to be intercalated with olivine-bearing basaltic flows.

The satellite cone and domes on the southeastern flank (Fig. 5) are well-preserved structures made up largely or entirely of olivine basalt scoria. The cone is about 300 m high, and has a shallow summit crater with a flat, swampy floor. The larger of the two domes has a shallow bowl-like depression on its highest point: this is either a small explosion crater or a collapse feature.

Only a few small planeze remnants remain on the northern and western slopes, and the gorges between them are generally untraversable. A short traverse in the middle reaches of the Laneme River, on the northern side of the complex was halted by slit gorges and house-sized boulders of massive, very coarse basaltic agglomerate. This agglomerate forms high, smooth cliffs, is almost completely unjointed, and is cut in many places by dykes, 50cm to 5cm thick, of fine-grained aphanitic olivine basalt. It consists of large angular to subangular fragments of dark grey to red or red-brown olivine basalt and light grey to red porphyritic andesite, in a gritty mottled red-brown and grey matrix. There appear to be no metamorphic effects at the contacts with the dykes. Float in the Laneme River includes olivine basalt, lesser olivine-hornblende-2-pyroxene andesite, and rare hornblende dacite.

The Anji River, in the southwestern part of the complex reveals a complete section through the volcanic sequence from basement rock to the youngest andesites. Basement is exposed at points 1514 and 1516 (Fig. 2)*, close to one of the dacitic subvolcanic intrusive masses: it consists of dark grey highly contorted shales cut by numerous quartz veins dipping generally about 82^{o}W/190^{o}. The deformation and quartz veining was probably caused by the nearby intrusion. The basement rocks are overlain by soft, weathered buff tuffaceous sandstone or tuff which dips gently west. The succession then is (west and upwards):

massive, coarse basaltic agglomerate (1517)
green-grey volcanolithic or tuffaceous sandstone (1516)
basaltic agglomerate (1521, 1522)
massive olivine basalt lava (1523)
volcanic rudite (1523)
vesicular olivine basalt flow, with irregular top (1525)
tuffaceous sandstone or tuff dipping 3^{o} West (1525)
massive volcanic breccia with angular fragments up to 1 m (1526)
thin flow of hornblende-2-pyroxene andesite (1527)
thin-bedded grey tuffaceous sandstone (1510)
olivine basalt agglomerate (fragments 5 cm to 1 m) (1510)
laminated tuffaceous sandstone (1528)
olivine basalt lava (1528)

---

* The outcrop area is far too small to be shown on the map.

In places (1518, 1520, 1524) this sequence is cut by massive dykes of hornblende-2-pyroxene andesite of uncertain (several metres) thickness. Total calculated thickness of the sequence is about 680 m.

Southern summit area, and northern caldera

The grassy, once glaciated northern summit area of the Hagen Range, with its relatively high proportion of outcrop affords far more information on the structure and history than the rest of the volcano. The area can be divided into two main geological units:

1. The early volcano, now represented by the remanent caldera walls and adjacent slopes.

2. The later central andesitic complex and subvolcanic plugs.

The bulk of the older rocks of the Hagen complex are porphyritic olivine basalts, and these are exposed over a wide area in the summit region. In the south, they are intercalated with hornblende-bearing andesitic flows and olivine-2-pyroxene and 2-pyroxene basalts of intermediate character. In the north, and in the remainder of the complex, the lavas are almost entirely olivine basalts.

Five principal lava types are distinguishable in the southern summit area (Fig. 2); these are:

1. Coarsely porphyritic olivine basalt

2. Olivine-hornblende-2-pyroxene andesite

3. Olivine ± hornblende-bearing 2-pyroxene basalt or low-Si andesite.

4. Porphyritic olivine basalt

5. Hornblende - olivine - 2-pyroxene andesite.

It is convenient to describe the summit area in terms of the glacial valleys which extend outwards from the caldera rim. There are numbered 1 to 6 from southwest to northeast in Fig. 2.

Type 1 olivine basalt crops out in the floor of valleys 1, 2, and 3, on the low northern part of the ridge between valleys 2 and 3, and in the caldera rim (Figs 6 & 7) at the heads of these valleys. The southeast part of the caldera rim is made up largely of olivine basalt, as is the remainder of the summit area, and the rest of the complex north of the ridge between valleys 5 and 6.

Type 2 andesite forms a large part of valley 4, the ridges on either side of it, the eastern side of valley 3 (Figs 5 & 6), the sides of valley 5, and much of the southern side of valley 6. The andesite overlies the type 1 olivine basalt with a sharp contact. It is closely related to the andesites of the central complex, and probably represents lava that spilled over the caldera rim during the formation of this complex.

Figure 8. Anji River (extreme left), plugs (left), central andesitic complex (centre), and internal glacial valley (right foreground). Part of southern crater wall at far right. Cloud covers the slopes above the Anji River gorge. Negs. GA5430, 5435, 5407, 5442.

The third lava type (3) is intermediate between types 1/4 and types 5/2, and directly overlies type 1 basalt. Around valley 1 and on the ridge between valleys 1 and 2; it is hornblende-bearing and in places (eg. head of valley 1-1731) is closer in mineralogy to the type 2 andesite than to the underlying olivine basalt. Farther west, hornblende is absent and olivine is more common. The basalt appears to overlie the type 2 andesite, and is overlain by type 4 olivine basalt wherever it occurs, except on the ridge between valleys 2 and 3 where the olivine basalt has been eroded away. The type 4 olivine basalt is similar to type 1 except that it is a little finer-grained, and a little less rich in ferromagnesian minerals. Small patches of olivine-2-pyroxene andesite with traces of hornblende occur on top of olivine basalt 4 on the outer ends of the ridges flanking valley 5. This andesite also occurs as small patches near the road just south of the satellite cone.

In places, such as the ridge crests flanking valley 4, gradual changes in the units can be traced. For example, there is a gradual increase in the amount of olivine in the type 2 andesite from bottom to top, and the contact with the overlying olivine basalt is gradational rather than sharp.

The central andesitic complex is separated from the basalts and andesites described above by a curved fault, or faults. It consists of pale grey porphyritic andesite with prismatic black hornblende phenocrysts and abundant white plagioclase phenocrysts 1-2 mm long. Near the caldera wall, the andesite contains appreciable amounts of olivine, but closer to the centre of the complex olivine disappears and tridymite becomes increasingly common. The presence of tridymite in these rocks can usually be detected in hand specimen by the characterisitc cavity-filling habit which gives the rock the appearance of having numerous small, irregular partly-filled vesicles. Slightly weathered specimens have a yellowish colour about these 'vesicles'.

Two small plugs of biotite-hornblende-2-pyroxene andesite or dacite which intrude both the olivine basalt infrastructure and the caldera-filling andesite form steep-sided hills in the headwaters of the Anji River (Fig. 8). The rocks making up these plugs are massive and almost lacking in joints, hence the strong cliff and gorge-forming characteristics. Their effects on the enclosing rocks have been described previously.

The northeastern part of the complex, that is the northern caldera, and adjacent craters, appear to be made up almost exclusively of olivine basalt flows and intercalated agglomerate, etc. The two northernmost craters, which are clearly not simple erosional features, are up to 1000 m deep, have very steep (70^{o} or more) walls and are sharply truncated on their western sides. A small craterlike feature near these two is an amphitheatreheaded stream valley, but its shape and extreme depth (ca 600 m) compared to its length suggest that it may at one time have been a small crater. The rounded embayment in the scarp near the microwave repeater station (Fig. 2) may also be a remnant of a crater because of its smoothly curved shape, but could also be an amphitheatre-headed valley. The nature of the small cone on the far northeast flank is unknown, apart from its form.

West of the repeater station, in the headwaters area of the Laneme River, is a roughly arcuate, scarp-like line of hills which partly encloses two low, rounded hills of coarsely porphyritic 2-pyroxene biotite-hornblende andesite/dacite. These hills probably represent eroded plugs similar to those in the head of the Anji River. Nearby a small inlier of Tertiary greywacke and shale crops out. Other rocks in the area, seen only as float, include vesicular and non-vesicular basalt and andesite, and rare dacite.

Pre-Hagen rocks

To the north, west, and south the Hagen complex is surrounded by gently to moderately folded Tertiary shale, greywacke, and limestone. The inlier between the Nok and Konup Rivers on the western side of the complex (Fig. 2) is entirely limestone. A high ridge of Oligocene-Miocene greywacke and shale, underlain by cliff-forming Eocene to Oligocene limestone and Palaeocene marl and shale, extends to the Nebilyer River on the southeast flank (Bain et al., 1970). These Tertiary sediments underlie most of the Hagen volcanic complex. The small inlier near the Gumanche River consists of thin-bedded shale, siltstone, and sandstone, probably of Upper Cretaceous age. Similar Cretaceous sediments, underlain by Lower Cretaceous greywacke and shale and Jurassic shale, underlie the extreme eastern flanks and eastern and southeastern aprons of the complex. Jurassic shales are exposed in the Paia River gorge in the northeast corner of the map area (Fig. 2). The Mesozoic rocks shown on the extreme top, right of centre of Fig. 2, are Jurassic shale and Upper Triassic metavolcanic rocks intruded by gabbro sills and dykes.

PETROGRAPHY

Olivine basalts (units 1 and 4)

The olivine basalts which make up the bulk of the Hagen complex are petrographically very uniform. There are only minor variations in the amount of ferromagnesian minerals, particularly olivine, and in the amount of magnetite (reflecting the oxidation state of iron). The rocks are dark grey to almost black, vesicular in places (tops of flows), and moderately to highly porphyritic. Phenocrysts of augite and olivine, equant in form and generally 1 to 3 mm in diameter, make up to 25 percent of the rock and are readily visible to the naked eye. Abundant prismatic plagioclase phenocrysts, generally about 1-2 mm long, are much less easily seen. Irregular to euhedral microphenocrysts of magnetite are rare. The groundmass is composed of small plagioclase laths (around 0.1 mm), augite grains, usually a few small olivine crystals, abundant fine-grained magnetite, interstitial potash feldspar, and a trace of apatite. Some specimens contain small amounts of orthopyroxene as tiny needles in the groundmass. Others contain a few small hypersthene phenocrysts (mantled by augite) as well; these grade into the olivine-2-pyroxene basalts. Rare olivine basalt specimens contain a trace of basaltic hornblende which is partly to completely replaced by fine-grained plagioclase, pyroxene, and opaque mineral. These grade into (olivine-) hornblende-2-pyroxene basalt and andesite with increasing amount of hornblende and hypersthene at the expense of olivine and augite.

Plagioclase phenocrysts are euhedral or subhedral, show only slight cumulative tendencies, and are slightly to moderately zoned. Zoning is from labradorite or bytownite cores, some of which are irregular, to oligoclase rims, and is usually modified by weak to moderate oscillatory zoning. Inclusions are present in most phenocrysts, ranging from a few very small opaque grains or augite grains, or both, to wide zones of small inclusions of fine-grained, opaque-rich groundmass. Glassy inclusions are rare. There is a rim of potash feldspar ranging from 0.001 mm to 0.02 mm wide on the phenocrysts. The groundmass laths are oligoclase-andesine, are moderately zoned to unzoned, and usually have narrow potash feldspar rims.

Augite forms large, commonly composite and rounded phenocrysts which are faint brown to green-brown and show slight zoning, and very small pale green to green-brown groundmass grains. The phenocrysts show a moderate to strong cumulative tendency, which may involve olivine. Twinning and hourglass structure are present but not common. Optical properties ($2V = 55-60^o$, anomalous interference colours) indicate a diopsidic augite composition with an appreciable alumina content; the pale colour in plane polarized light suggests that Ti content is low to moderate.

Olivine forms phenocrysts, generally 0.5 to 3 mm across, with a moderate cumulative tendency. Some olivine is clumped with or included in augite phenocrysts or groups of phenocrysts. It also forms small euhedral crystals in the groundmass of some specimens. Rarely there are narrow, extremely fine-grained pyroxene rims on the smaller olivine grains: these rims are more common in specimens with appreciable amounts of hypersthene. Composition is close to FO_{80}, as indicated by the 2V of near 90^o, usually negative.

Magnetite occurs as tiny euhedral crystals in the groundmass, and as scarce microphenocrysts. Many of these microphenocrysts are aggregates of groundmass crystals. Reflected light examination of a small number of specimens shows that the magnetite is largely homogeneous; lamellae and blebs of ilmenite are very rare.

Potash feldspar forms narrow rims on plagioclase and tiny interstitial patches in the groundmass. It is distinguishable in thin section by its very low relief, faint pinkish tinge, and sharp contacts with plagioclase. Where optical properties could be measured, it has very low negative 2V, indicating sanidine structure.

Olivine-2-pyroxene basalts and low-Si andesites (unit 3, Fig. 2)

The 2-pyroxene basalts are much more variable than the olivine basalt, and have features of both the olivine basalt and the hornblende-bearing andesites. They consist of small phenocrysts of plagioclase, augite, hypersthene, and minor olivine in a groundmass of plagioclase, augite, hypersthene, magnetite, a little olivine, a trace of potash feldspar, and accessory apatite. Basaltic hornblende phenocrysts, variably replaced by extremely fine-grained pyroxene, plagioclase and magnetite, occur in some specimens from low in the unit. The low-silica andesites have more hypersthene and plagioclase and less augite and olivine than the basalts, but there is no clear dividing line between them.

Plagioclase (50 to 65%) forms euhedral phenocrysts up to 1.3 mm, rarely to 2 mm, and generally around 0.5 mm long. They are moderately zoned from labradorite to oligoclase, and generally have zones or cores rich in minute dark groundmass inclusions. Narrow potash feldspar rims occur on the phenocrysts in some specimens. The groundmass laths are less than 0.1 mm long.

Augite (10 to 25%) is similar to that in the olivine basalts. It forms euhedral to subhedral prisms, is weakly to moderately glomeroporphyritic, and commonly contains relict cores of hypersthene or mantles it. In several specimens ragged augite inclusions occur in hypersthene phenocrysts. Augite also forms small pale green groundmass grains, and occurs in pyroxene rims on olivine.

Hypersthene (5 to 20%) forms elongated euhedral prisms, both as phenocrysts and in the groundmass. Some phenocrysts and micro-phenocrysts have rims of augite or contain augite inclusions; some occurs as irregular cores in augite phenocrysts. It also forms fine-grained granular rims on olivine with augite, or partly replaces olivine as coarser-grained aggregates with augite and magnetite. In some phenocrysts minute lenticular exsolution lamellae of clinopyroxene can be seen; these are generally concentrated in the core. The orthopyroxene is moderately to strongly pleochroic from pale pink to faint green, and has a high negative 2V.

Olivine (trace to 10%) is similar to that in the olivine basalts, but is either rimmed or partly (10%) to wholly replaced by pyroxene and magnetite.

Hornblende (0 to 5%, orig. up to 8%) forms phenocrysts up to about 3mm, generally as elongated prisms or bladed crystals. It is variably replaced from the rims inwards by very fine-grained pyroxene, plagioclase, and magnetite. Many crystals have a narrow, dark very fine-grained inner rim, and a coarser-grained, less opaque-rich outer one. Some phenocrysts have been completely replaced, and the 'ghosts' commonly have a core of still coarser-grained pyroxene, plagioclase, and magnetite. Pleochroism scheme is α very pale yellow-brown, β yellow-brown, and γ deep yellowish brown to red-brown: it is basaltic hornblende.

Potash feldspar occurs in the same form as in the olivine basalts, but in smaller quantities.

Andesites and dacites

The andesites and (rare) dacites are even more variable in petrographic character than the 2-pyroxene basalts, although they all appear rather similar in the field and in hand specimen. They contain phenocrysts of plagioclase, microphenocrysts of magnetite, and phenocrysts of either:

augite and hypersthene
hypersthene, augit, and minor hornblende
hornblende and lesser hypersthene and augite ± biotite, or
hornblende and biotite ± minor hypersthene and augite (uncommon)

Relict olivine phenocrysts are present in some specimens, generally the most mafic, silica-poor types. Quartz phenocrysts occur in only three specimens, two from the plugs in the headwaters of the Laneme River (which are described below), and one from float in the same river. The fine-grained groundmass consists of tiny prisms and needles of ortho and clinopyroxene, and fine-grained magnetite in a mosaic, or felted mass of laths of plagioclase. Groundmass hornblende is present in most specimens. Patches of tridymite are present in the groundmass of several specimens from the central complex and in a few from flows outside the southern caldera rim. Vestigial rims on plagioclase and minute interstitial amounts of potash feldspar occur in some specimens.

The olivine-bearing andesites grade with the disappearance of hornblende and hypersthene and increase in the amount of olivine and augite into olivine basalt. This progression is shown well in the ridge between valleys 3 and 4. Olivine basalt 1 (1739 - 42) is overlain by:

1. andesite with 2% hornblende, 1% olivine (1743)
2. andesite with 10% hornblende, 3% olivine (1745)
3. andesite with 5-7% hornblende, 5% olivine (1747)
4. basalt with 2% hornblende, 8% olivine (1748)
5. basalt with a trace of to no hornblende, 10% olivine (1749-50)

The plugs in the headwaters of the Anji River are composed of andesite with large (up to 5 mm) phenocrysts of plagioclase, and smaller phenocrysts of hornblende and minor biotite and magnetite in a very fine-grained groundmass of plagioclase, augite, hypersthene, hornblende, magnetite, and accessory apatite. Those in the headwaters of the Laneme River (1790) are similar, but contain up to 10% biotite, mainly as phenocrysts, a small amount of quartz mainly as small, rounded, embayed phenocrysts, and in places up to 1% olivine, rimmed by magnetite and hornblende.

Plagioclase in the andesites occurs as large (generally 1-5 mm) euhedral phenocrysts and very fine-grained mosaics or felted aggregates of laths in the groundmass. The phenocrysts are strongly zoned from andesine, labradorite, or even bytownite in the core, depending largely on the size of the phenocryst, to oligoclase at the rim. Zoning is normal overall, but moderately to strongly oscillatory in detail. Composite and clumped phenocrysts are common, and most have inclusions ranging from rare hornblende and pyroxene grains to densely packed zones or cores of dark, extremely fine-grained groundmass material. Groundmass crystals show moderate to strong normal zoning, and in some specimens are rimmed by alkali (potash?) feldspar.

Augite (3 to 20%) occurs as small (about 0.5 mm) euhedral phenocrysts and tiny faint green to yellow-green groundmass prisms and needles. The phenocrysts are pale green brown to faint green, commonly clumped together, and comprise up to 10%, but generally 5% or less, of the rock. A few phenocrysts have cores of hypersthene. Augite also occurs as rims on hypersthene and in rims and mantles on olivine.

Hypersthene (3 to 20%, gen. 10-15%) forms 0.5 mm euhedral phenocrysts and tiny elongated groundmass prisms. The phenocrysts are moderately to strongly pleochroic, commonly contain minute clinopyroxene exsolution lamellae, and are less commonly rimmed by augite. Augite rims, particularly on smaller hypersthene crystals, are in many cases confined to the longer sides (100, and less notably 010 faces) and absent from the ends of the prisms. This feature is common to all the Highlands volcanoes.

Hornblende (2 to near 30%) forms euhedral phenocrysts from 0.5 to 5 mm long (generally 1-3 mm), and small euhedral groundmass prisms. Most of it has fine-grained pyroxene-magnetite-plagioclase rims of various widths. In some specimens, the smaller crystals are completely replaced, and in a few, the phenocrysts are largely to completely replaced by pyroxene-magnetite-plagioclase aggregates. Typical pleochroism schemes are:

1. α = pale yellow brown, β = yellow-brown, γ = deep yellowish brown or red-brown.

2. α = pale greenish yellow-brown, β = greenish brown, γ = dark greenish brown.

3. α = pale greenish yellow-brown, β = brownish green, γ = dark brown-green.

4. α = v. pale straw, β = pale green, γ = green or deep bluish green.

Zoning is common, and is best seen in sections parallel to γ. Generally, the more abundant the amphibole, the greener, or less oxidized it is, and the narrower its opaque-rich rim is, though there are several exceptions. There is also a tendency for the less oxidized hornblendes to occur in the most siliceous rocks; the most oxidized, most heavily replaced ones are most common in the most basic andesites.

Hornblende in the plugs in the Anji River is green-brown and has narrow opaque-rich rims. The more siliceous plugs in the Laneme River area have zoned, rimless hornblendes with the following pleochroism:

unoxidized rock - α = pale yellow-brown, β = dark brown-green, γ = deep, slightly brownish to bluish green.

oxidized rock - α = straw yellow, β = very dark yellowish red-brown, γ = extremely dark red-brown.

The changes in colour from green to brown and red-brown indicate a change from common to oxidized or basaltic hornblende.

Biotite occurs in the Anji and Laneme plugs, and in one lava outcrop in the Anji River (1521). It occurs as phenocrysts up to over 2 mm wide, and, in one specimen (1790 B) as small flakes in the groundmass. In the Anji plugs it is surrounded by hornblende, in the Anji lava it has narrow magnetite-rich rims. Biotite in the Laneme plugs has hornblende mantles in places; in other places it shows some breakage and shredding. Pleochroism is pale to very pale yellow-brown to dark or very dark brown, or greenish brown.

Olivine occurs in small quantities as phenocrysts (up to 3 mm) and rare smaller crystals in many of the andesite specimens. In the most basic types, some has narrow pyroxene + magnetite + plagioclase rims; these rims become wider and more common as silica content of the lavas increases, and olivine is finally completely replaced in the acid andesites. The replacing minerals are hypersthene and usually magnetite commonly with augite $\pm$ plagioclase. Composition of the olivine is close to Fo_{80}, the same as in the olivine basalts. The presence of olivine in andesitic rocks, some of which contain modal free silica (tridymite), is clearly not an equilibrium phenomenon, as testified to by the pyroxene rims. It is probably relict olivine originally crystallized in a basaltic magma which has since differentiated.

Magnetite occurs commonly as small microphenocrysts, generally clumped with pyroxene or amphibole, as fine groundmass 'dust', and in the rims on hornblende. The microphenocrysts are generally homogeneous titanomagnetite, whereas the smaller crystals contain up to 50% ilmenite lamellae, the amount of ilmenite increasing as the size decreases, and as the rock becomes more siliceous. There is a small amount of maghemite in a few specimens, and trace amounts of ilmenite (?) needles in some rocks.

Tridymite forms patches of wedge-shaped, commonly radiating twinned crystals, or equigranular mosaics (recrystallized ?) up to over 1 mm across in the groundmass of a few andesites, and in most of the dacites. Individual crystals are up to 1 mm or more long. In a few specimens (1512, 1786) some occurs as rounded radial aggregates attached to the walls of cavities. It is suspected that some of these cavities are gaps left in the thin section after tridymite has been plucked out during grinding.

Apatite forms stumpy to highly elongated prisms up to 0.3 mm long. It is far more common in the andesites than in the basalts, and appears to increase in quantity with increasing SiO_2 content of the host rock. Larger crystals not enclosed in phenocrysts are usually brown or pinkish brown and pleochroic, owing to abundant inclusions of ?hematite; some have an almost black outer zone or rim.

Country rock inclusions

Inclusions of shale, siltstone sandstone, amphibolite, gneiss, diorite, gabbro, basalt, and quartz have been observed in the Hagen lavas. They are very rare in the olivine basalts, but quite common in the andesites; however the degree of reaction with the magma is slight. The only inclusions examined in thin section are:

1. altered and partly recrystallized hornblende diorite or gabbro (in biotite-hornblende andesite - 1521),

2. Hornblende-pyroxene diorite in hornblende-2-pyroxene andesite, and

3. mixed hornblendite-pyroxenite in hornblende-2-pyroxene andesite from the central andesite complex - 1789.

The hornblendite in the last type consists of basaltic hornblende (α very pale brown, β deep yellow-brown, γ deep greenish yellow-brown) with magnetite rims, some corroded augite cores, and interstitial plagioclase containing abundant apatite. The pyroxenite, which has a gradational contact with the hornblendite, consists of highly corroded, inclusion (hornblende, opaques)-riddled colourless augite, variously replaced by opaques, interstitial hornblende, and a trace of opatite. The augite shows anomalous blue interference colours and moderate to strong dispersion, and has a 2V of about 65°: it is probably aluminous diopside or diopsidic angite.

CHEMISTRY

Jakeš & White (1969) analysed five rocks from Mount Hagen, and Mackenzie & Chappell (1972) discussed preliminary work on the Highlands volcanoes, including Mount Hagen, and present three new analyses of Hagen rocks. The analyses (Table 2) show that the lavas range from high-K olivine basalt, or shoshonite, to high-K low-silica andesite and high-K andesite. Some of the rocks described in the previous section are dacites, possibly high in potassium, with silica contents up to 65% or more. It is planned to analyse at least 35 rocks collected from the Hagen complex during the 1970 and 1971 field seasons.

MOUNT IALIBU

GEOGRAPHY

Mount Ialibu is near the northern border of the Southern Highlands District with the Western Highlands District, and on the southern side of the main central ranges. It is about 45 km south-southwest of Mount Hagen town (Fig. 1). Ialibu Sub-District Headquarters is on the southwest flank of the mountain (Fig. 9), and Pangia Patrol Post is on its southwest flank. These centres are linked together and to Mount Hagen and Mendi (40 km to the west-southwest) by road. At the time of the survey, a new road between Mount Hagen and Mendi, which will greatly improve access to Ialibu, was under construction. This road passes along the base of the northwestern flank of Mount Ialibu. Ialibu town is served by regular government charter flights from Mount Hagen, and the airstrip is also used by aircraft serving local missions.

Population is moderately dense around the northwestern, western, southwestern, and low southeastern flanks. Tracks are numerous and many on the northwestern and western sides extend up the broad stream valleys towards the summit of the mountain (Grago, Ko, Ilge, and Iale Rivers, Torbele Creek). A track leads from Ko village to the summit survey marker (3465 m) and the Posts and Telegraphs microwave repeater station, where there is a helicopter landing pad. Helicopter landing places are numerous in the populated areas, but non-existent on most of the eastern flanks; only the broad stream draining north to the Kaugel River offers sufficiently broad gravel banks.

MORPHOLOGY

Mount Ialibu is morphologically complex, and shows some interesting contrasts in styles of erosion. The main, southern part of the complex is made up of steep forested ridges separated by broad, largely cultivated or grassy alluvium-floored valleys, changing headwards into steep V-shaped valleys on the western side, and extremely rugged ravines and gorges on the eastern side. Outwash from the mountain has modified the topography on the western side, with the ridges sloping down abruptly to almost flat grassy alluvial plains and gently sloping alluvial fans (e.g. Ilge River, at Marale village, Figs 9 & 10). The alluvium extends almost to the heads of the Grago, Ko, Ilge, and Iale Rivers, close to the summit area. On the southern side, the deeply eroded ridges slope steeply down to a gently southward-sloping constructional

Table 2 - analyses of specimens from Mount Hagen

	1	2	3	4	5	6	7	8
SiO_2	51.74	52.27	52.41	53.74	54.24	54.81	55.45	57.66
TiO_2	1.16	0.98	1.06	1.05	0.09	1.10	0.75	0.73
Al_2O_3	16.78	14.98	16.01	15.84	15.32	15.10	18.87	18.87
Fe_2O_3	3.32	1.82	5.10	3.25	1.60	2.59	2.60	4.44
Fe O	5.23	6.40	2.96	4.85	6.39	6.28	3.60	1.84
MnO	0.13	0.16	0.15	0.11	0.15	0.15	0.13	0.13
MgO	6.39	8.71	7.12	6.36	8.11	6.14	4.26	3.92
CaO	8.81	8.87	7.62	7.90	7.03	8.62	5.19	4.86
Na_2O	2.46	2.63	3.13	2.38	2.76	2.26	2.55	2.50
K_2O	2.32	2.16	2.21	2.57	1.66	2.71	2.39	2.76
P_2O_5	0.64	0.55	0.51	0.54	0.32	0.69	0.44	0.40
H_2O^+	) 0.75	0.52	0.86	) 1.09	0.75	) 0.25	) 3.32	) 1.35
H_2O^-	)	0.22	0.68	)	0.49	)	)	)
CO_2	n. d.	0.19	0.08	0.02	0.05	0.01	n. d.	n. d.
Total	99.73	100.46	99.90	99.70	99.77	100.45	99.55	99.36

Analyses 1, 4, 6-8 - Jakeš & White (1969)

Analyses 2, 3 and 5 - Mackenzie & Chappell (1972)

1. High-K olivine basalt*, Kugogi, 144°10'E 5°43'S.
2. High-K olivine basalt*, southwestern summit area (10NG 1319)
3. High-k olivine basalt*, Turuk River, Mt Hagen-Wabag road (10NG 0600)
4. 'Augite shoshonite', Gumanche River
5. Hornblende-olivine high-K low-Si andesite, southwestern summit area (20/1320)
6. 'Augite shoshonite', Kugogi, 144°10'E 5°45'S
7. 'Amphibole-augite shoshonite', Baiyer River 144°10'E 5°40'S
8. 'Amphibole-augite banakite', Baiyer River 144°10'E 5°40'S.

*Alternatively, 'shoshonite' (Joplin, 1968).

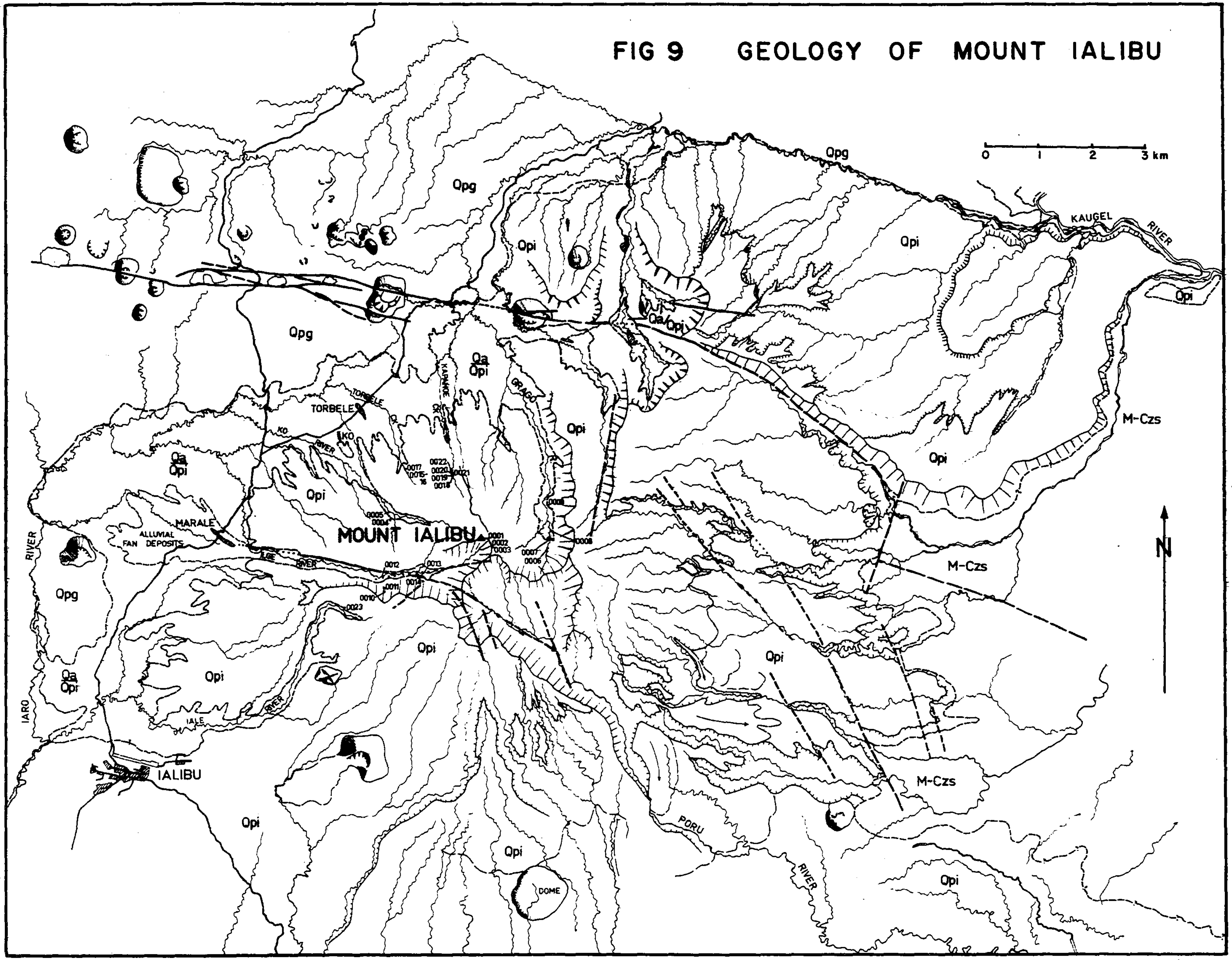


FIG 9 GEOLOGY OF MOUNT IALIBU

To accompany Record 1973/89

B55/A9/15

Figure 10. Mount Ialibu from the air, to the west. The abrupt junction of eroded ridges and alluvium can be seen at centre. Valley above radio box is the Ilge River valley. In the distance are other Quaternary volcanoes, Mount Karimui (at left), and Mounts Duau and Favenc (far right). Neg. GA/5437.

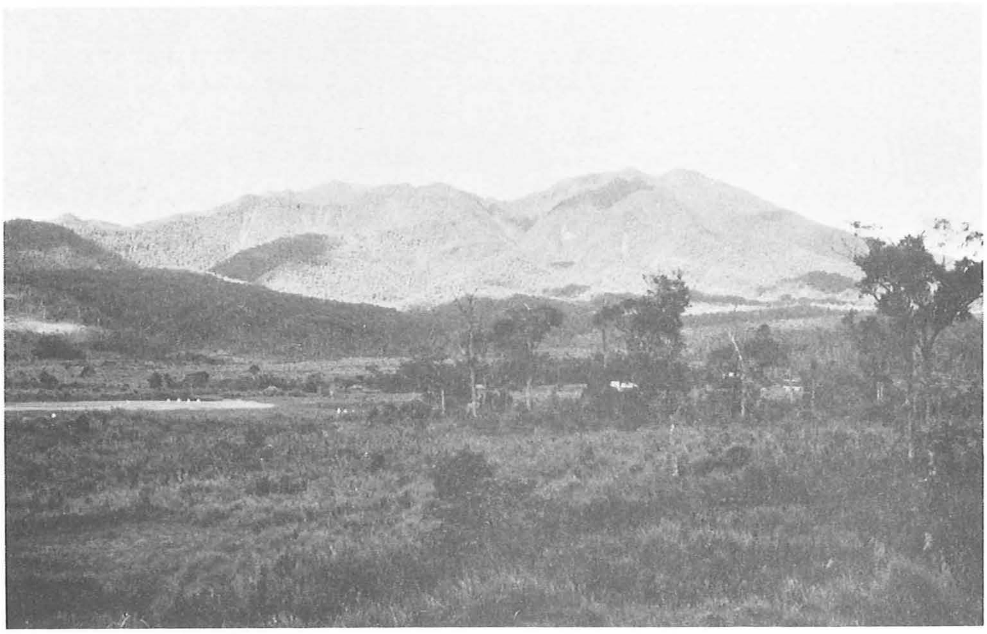


Figure 11. Mount Ialibu from Ialibu Government station, to the southwest. The deeply eroded, rugged nature of the mountain can be seen. Neg. GA/5452.

surface slightly to moderately dissected by small gullies and valleys (Fig. 11B). A prominent satellite cone and a low, broad dome break the otherwise smooth southern slopes. These smooth slopes end abruptly at the Poru River, which has cut a huge gorge in the southeastern flank of the mountain, and a vertical-walled ravine in the lower slopes. To the north of the Poru River, the slopes are moderately to deeply dissected by numerous large streams, some of which have cut deep gorges or valleys flanked by cliffs. However, several flow features such as flow fronts still remain. The eastern edge of these slopes is a scarp 100 to 300 m high, embayed by deep ravines which end usually in high waterfalls. These ravines open eastward on to the relatively subdued topography developed on the Cretaceous and Paleocene shales.

Separating the northern from the southern part of the volcanic complex is a curved, fault-controlled valley which at its eastern end turns into a gorge up to 500 m deep. Immediately to the south of the central part of the fault zone (Fig. 9) is a crater-like, almost flat-floored valley; to the north is a similar valley which may represent the other half of the crater. About 2 km to the west is another small scarp resembling part of a crater wall, and to the northwest of that is a triangular planeze remnant with a small satellite cone on its eastern side. Farther west along the fault zone, and on either side of it are a large number of cones with summit craters, maars, domes, and four small lakes on the gently undulating Giluwe volcanic field (Qpg). The cones actually straddling the fault zone have been broken up by small lateral and vertical movements of 100 m or so. The lakes were formed in fault-bounded depressions resembling rift valleys.

The unfaulted northern part of the Ialibu complex slopes at about 25° to 30° to the deep river valley which marks the northern limit of the Ialibu volcanics. The constructional slopes are deeply dissected by numerous ravines, leaving planeze remnants on the highest parts in the southwest corner, and on the lower eastern side. Streams on these planeze surfaces have cut only small ravines, but occupy ampitheatre-headed valleys up to 400 m deep below the edge of the planeze. The heads of these valleys are near-vertical and form spectacular waterfalls up to over 300 m high.

GEOLOGY

Because of the very poor outcrop in most parts of the Ialibu complex, its geology is poorly known. It appears that the most basic olivine-bearing lavas come from the highest parts of Mount Ialibu itself, whereas lavas in the lower parts to the north of the summit are andesitic. Hornblende-bearing lavas were found at only one locality, in the headwaters of Kapanoe Creek (0018-22, Fig. 9).

The Ialibu lavas are rather uniform in appearance, with 1-5 mm white plagioclase phenocrysts in a medium to dark grey groundmass. Pyroxene and olivine phenocrysts are not prominent, but hornblende phenocrysts up to 4 mm long are plainly visible in the hornblende andesites.

Outcrop in the summit area (0001-3) is olivine-bearing and olivine-free basic andesite. The olivine-bearing rock is light-medium brownish grey, with prominent 1-2 mm black pyroxene and much less prominent 1-2 mm plagioclase phenocrysts. The olivine-free rock is dark grey and finely vesicular, with no prominent phenocrysts.

Lavas from the head of the Ilge River, west of the summit, are intermediate to moderately acid pyroxene andesites. Rocks from float in the nearby head of the Iale River (0023) are olivine basalt, olivine-bearing pyroxene andesite, and pyroxene andesite. This is the only locality where abundant olivine basalt was found. Float from the head of the Ko River west-northwest of the summit (0004-5) includes olivine basalt and pyroxene andesite. Pyroxene andesite crops out in the Torbele River (0015-17) and the Grago River, northwest and east of the summit respectively, while in Kapanoe Creek, outcrop is dark porphyritic hornblende-pyroxene andesite and minor pyroxene andesite.

Faulting is intense in the summit region, where there are numerous small faults and large joints associated with a major fault which controls the Ilge and upper Poru gorges, and may continue to the southeast corner of the map area (Fig. 9). Several faults with small lateral and vertical movements, as evidenced by small scarps and displaced erosional scarps and streams, cut the eastern flanks. A fault with a larger vertical displacement appears to control the stream valley east of the Grago gorge. To the north of this fault is the fault zone which cuts the whole complex, as described above. There has clearly been a vertical movement of at least 200 or 300 m on this fault zone before the formation of the field of small cones at its western end. Reactivation of the fault zone has produced further small vertical and lateral movements.

To the west of Mount Ialibu are extensive areas of outwash, ranging from coarse boulder gravel in the narrow stream valleys and upper parts of the fans, to finer gravel, sand, and silt farther away from the mountain. This outwash presumably overlies volcanic rocks from Mount Ialibu. Farther west and northwest and to the north are the hummocky volcanic deposits of Mount Giluwe, the summit of which is 30 km northwest of the summit of Mount Ialibu. East of the Ialibu complex are strongly faulted Upper Cretaceous to Palaeocene shale, siltstone, and sandstone, and Eocene to Miocene limestone, marl, and shale. The limestone etc. underlie the whole of the southern apron of Mount Ialibu.

PETROGRAPHY

The lavas of Mount Ialibu are mainly highly porphyritic 2-pyroxene andesites characterized by abundant prismatic plagioclase phenocrysts 1 to 5 mm long. Other rock types are shoshonite (high-K olivine basalt), olivine-2-pyroxene high-K basalt and low-Si andesite, and minor hornblende-2-pyroxene andesite.

The 2-pyroxene andesites consist of plagioclase phenocrysts (15 to 40%, generally about 20%, by volume), much less common smaller augite and hypersthene phenocrysts, and magnetite microphenocrysts, in a moderately fine-grained groundmass of the same minerals plus a small amount of potash feldspar and accessory apatite. Several rocks contain interstitial glass (2 to 15%), and a few contain small patches of tridymite (trace to 3%). One rock contains a few small pyroxene-rimmed olivine phenocrysts. Plagioclase makes up about 60 to 80 percent of the rock by volume (generally 70 to 75%), augite 5 to 20 percent (generally 10-15%), hypersthene 7 to 17 percent (generally 10-12%), magnetite 3 to 5 percent, and potash feldspar a trace to 4 percent (generally 1-2%).

The shoshonites and olivine-2-pyroxene high-K basalts and low-Si andesites consist of abundant (12 to 35%) plagioclase phenocrysts and small olivine (2 to 10%) and augite (trace to 6%) phenocrysts in a groundmass of plagioclase, augite, hypersthene, magnetite, olivine, potash feldspar, and accessory apatite. Hypersthene phenocrysts are present in the olivine-2-pyroxene rocks, which contain 5 to 8 percent modal hypersthene; the shoshonites contain only 1 to 2 percent hypersthene. Percentages of other minerals are: plagioclase 55 to 65 percent, augite 10 to 22 percent, olivine 4 to 15 percent, magnetite 4 to 7 percent, and potash feldspar 1 to 3 percent.

The hornblende-2-pyroxene andesites consist of the usual abundant (17-25%) plagioclase phenocrysts, and hornblende (8-12%) and hypersthene (2-3%) phenocrysts in a fine to very fine-grained groundmass of plagioclase, hypersthene, augite, magnetite, potash feldspar (trace to 1%), accessory apatite, and generally a small amount of hornblende. One rock contains a trace of tridymite. The hornblende is variably replaced by fine-grained pyroxene and magnetite, so that in some rocks only a third to a quarter of the original amphibole remains. The degree of replacement increases upwards in the sequence exposed in Kapanoe Creek (0018-22):

Locality	Original hornblende	Hornblende present
0018	12%	3%
0020	10-12%	3-4%
0021	10%	7%
0022	10-11%	10-11%

This progression is a result of the increasing loss of volatiles (O_2, H_2O) towards the top of a thick lava flow, or sequence of thin flows extruded in rapid succession. The amphibole is a normal basaltic hornblende with the pleochroism scheme: α = light yellow-brown, β = very dark yellow-brown, zoned, γ = deep to medium yellow-brown.

Plagioclase in the Ialibu lavas forms moderately to strongly zoned phenocrysts 0.3 to 5 mm long, and very small laths or minute polygonal grains in the groundmass. The phenocrysts are generally about 1 mm long, and are commonly composite. Some phenocrysts contain a few scattered inclusions, others contain narrow to broad zones or cores packed with inclusions; a few are clear, and a few are completely sieved with inclusions. The inclusions are either fine-grained dark groundmass, small pyroxene grains, or small magnetite grains. Zoning is normal overall with superimposed weak to strong oscillatory zoning.

Augite occurs as generally small (0.2 to 1 mm, rarely up to 2 or 3 mm) but not abundant phenocrysts in most rocks, and as small prisms, granules, and needles in the groundmass. It commonly mantles or has a core of hypersthene. Needles in the groundmass are packed with opaque inclusions in some rocks.

Hypersthene forms prismatic phenocrysts 0.2 to 2.8 mm long, averaging between 0.4 and 1.5 mm, and very small prisms and needles in the groundmass. Phenocrysts are commonly clumped, with or without augite, plagioclase, and magnetite, and some have mantles of augite. Smaller lath-like phenocrysts are commonly sandwiched between two narrow strips of augite. The hypersthene is weakly to moderately pleochroic in pale pinks and greens.

Olivine (4 to 15%) occurs as phenocrysts 0.1 to 1.7 mm across, averaging about 0.3-0.5 mm, and as smaller groundmass grains. It is commonly partly altered to bowlingite or iddingsite. Some phenocrysts are clumped together to form aggregates up to 2 mm or more across. In the most olivine-rich rocks, the shoshonites, olivine has no pyroxene rims; in rocks with less olivine amd more hypersthene, it has fine-grained pyroxene rims, forms cores or irregular inclusions in pyroxene, or has opaque-rich rims, and may also be charged with opaque inclusions. In olivine-2-pyroxene high-K basalt and low-Si andesite with more than 5 percent hypersthene, olivine appears to have mantled and partly replaced hypersthene, which commonly also has olivine inclusions near the rim. The olivine in these rocks also generally has a fine-grained pyroxene rim. In one rock, the olivine mantling hypersthene is aggregated with augite, and olivine also mantles augite.

Magnetite (3 to 9%) occurs as microphenocrysts or irregular clumps of small grains, generally in close proximity to pyroxene, olivine, or hornblende phenocrysts, in all except the most olivine-rich rocks. It also forms small to minute euhedral crystals in the groundmass.

Potash feldspar (trace to 4%) occurs as narrow (0.001 to 0.02 mm) rims on plagioclase phenocrysts, and on groundmass plagioclase in rocks with a relatively coarse-grained groundmass. It also occurs in small quantities interstitially in the groundmass of most rocks.

Tridymite (up to 3%) forms clumps of wedge-shaped crystals up to over 1 mm across in a few of the most siliceous andesites.

DISCUSSION

The Mount Ialibu lavas are notably different from those of Mount Hagen, with its predominant olivine-rich shoshonites. They also differ markedly from lavas from nearby Mount Giluwe, which is made up almost entirely of fine-grained hypersthene-bearing shoshonites. The abundance of large plagioclase phenocrysts and the rarity of olivine and pyroxene phenocrysts suggests that the Ialibu lavas are the products of prolonged crystal fractionation involving removal of olivine and augite from a parental shoshonitic magma. The apparent restriction of shoshonitic lavas to the top of the volcanic pile indicates that no parental magma came directly to the surface, but simply followed the andesitic magmas as successively lower parts of the differentiated magma chamber were tapped. It is not possible from the petrographic data alone to estimate the depth at which this magma chamber was located.

DOMA PEAKS AND MOUNT NE

GEOGRAPHY

Doma Peaks and Mount Ne are in the Southern Highlands district about 25 km east-southeast of Tari, an Administration sub-district headquarters. Tari is linked by regular and chartered light aircraft flights to several centres including Mount Hagen, and by road to Koroba, 27 km northwest, and to Tigibi mission at the foot of Doma Peaks (Fig. 12). A road connecting Tari with Mendi (Fig. 1) via Tigibi is nearing completion. It will pass over the saddle between Doma Peaks and Mount Ne.

The plains west of Doma Peaks and the stream valleys on its western flanks are densely populated and tracks are numerous. It is possible to walk up the Arua River at times of low water as far as the eastern crater wall, but the rest of the mountain is extremely rugged, forested, and almost inaccessible. Helicopter landings can be made on the lahar area in the crater, on the summit, and on several of the grassy areas on the eastern and southern sides of the mountain. It is possible to land in numerous places on the western side of the mountain: in villages, gardens, and on stream gravel banks. Access to Mount Ne is by helicopter, landing on grassy areas all around the mountain, or by road if and when it is trafficable.

MORPHOLOGY

Doma Peaks is markedly asymmetrical, with a smoothly sloping eastern side slightly to moderately dissected by radial drainage (Fig. 15), and a deeply eroded, very rugged western side which slopes abruptly to an almost flat apron (Tari valley). Remnants of flow fronts can still be seen on the eastern flanks, and the streams have cut valleys only a few tens of metres deep. The remainder of the mountain is cut by almost vertical-sided gorges up to 800 m deep. The streams occupying these gorges all drain to the west, so that the roughly flat-topped ridges between them are all eventually directed to the west and slope sharply to the western plain, resembling the spread fingers of a hand. The gorges change gradually downstream into broad flat-floored valleys with very steep walls, then open out on to the Tari valley.

North and south of the 'peaks' themselves (Ambua, Doma, and Lema, as they are known locally) in the headwaters of the Piwa and Huria Rivers, are eroded scarps up to 300 m high (Fig. 12) which are probably the remains of an old U-shaped caldera. The eastern wall of this caldera probably coincides with the eastern crater wall on which the survey marker stands, at 3530 m above mean sea level. In the headwaters of the Huria River, parts of this old scarp are buried by younger lava flows which originated from the present 'crater' or solfataric area just west of the summit. These flows have recognizable flow fronts and compression ridges still preserved, and are probably the same age as those on the eastern flank of the complex.

Inside the old caldera is a younger, much higher U-shaped scarp which is divided by a low saddle at the head of the Arua River into a northern scarp (Ambua, Figs 12, 14) and an eastern scarp (Lema, Figs 12 & 13).

These scarps are up to over 1000 m high, and are probably the eroded remains of a large crater. The area between them has a subdued topography, dominated by a hummocky lahar tongue (Fig. 14), covered only by shrubs and grass, which stems from the foot of the eastern crater wall and ends abruptly at the Arua River. There is a distinct level about 50 m above the bed of the Arua River below which the vegetation has been stripped away and secondary growth now occurs. It can be traced from the nose of the lahar to the point where the valley of the Arua River opens out onto the Tari valley. The stripping was probably caused by a nuée ardente, possibly related to the local legends of volcanic eruption reported by Glasse (1963). Alternatively it may have been caused by violent flooding of the Arua River after its dammed-up headwaters had broken through the nose of the lahar. However, there is no evidence that a lake was ever present in this area.

The northern part of the Lema scarp, at the head of the lahar, appears to be the most nearly purely volcanic in origin of all the scarps. It is the site of the most recent volcanic activity and is an active solfataric area (Taylor, 1971). It may also be related to the flows in the headwaters of the Huria River which cover the southern end of the Lema scarp and part of the older scarp to the south.

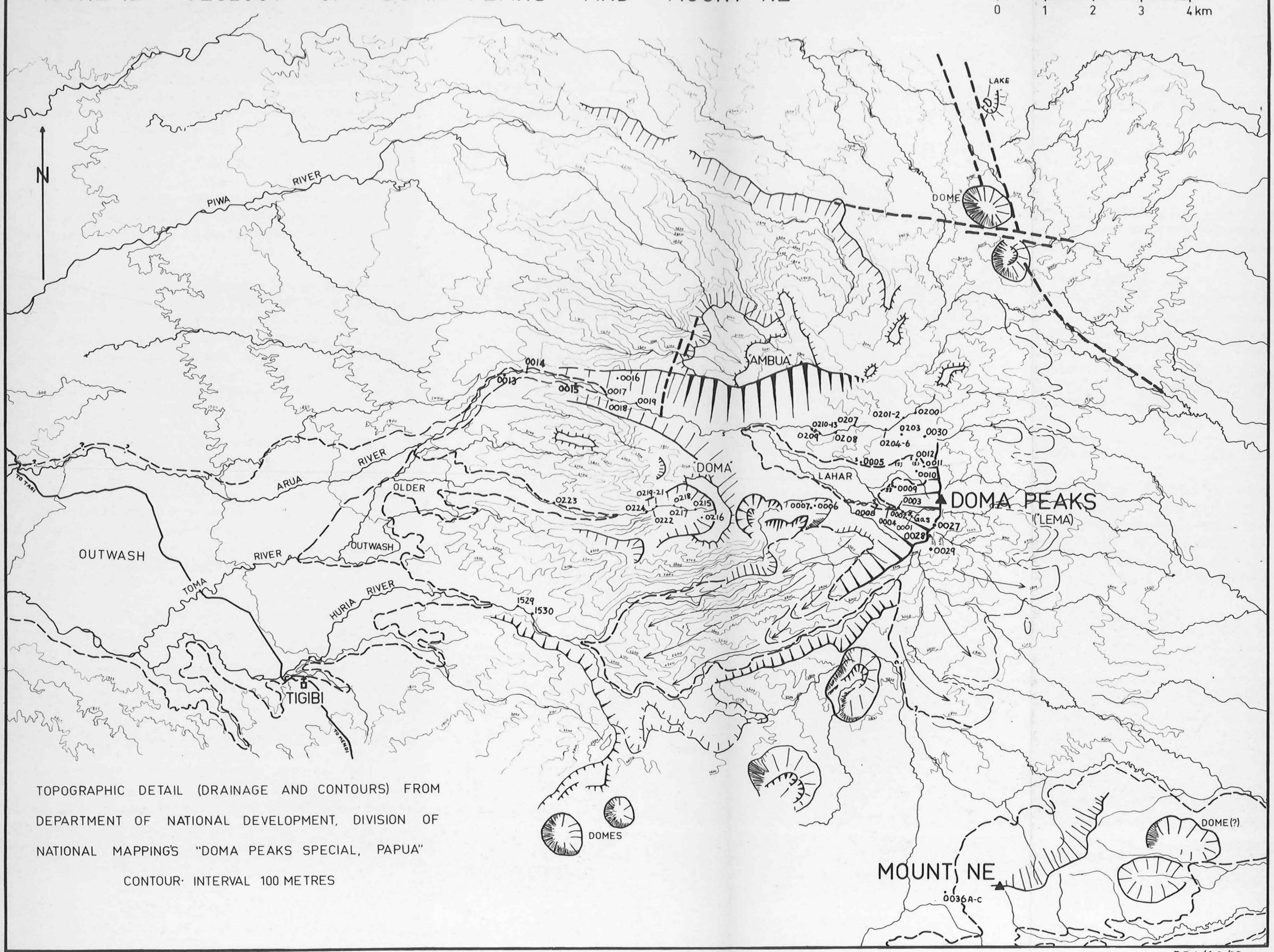
The western half of the Ambua scarp probably represents part of the old crater wall, and the eastern half one wall of the gorge cut by the Arua River after it broke through the western crater wall. This reconstruction is in harmony with the attitudes of the planeze or flow surfaces on Ambua (Fig. 12). North of the Ambua scarp, the complex is cut by several deep ampitheatre-headed valleys with near-vertical walls up to 600 or 700 m high. Waterfalls up to 300 m or more high occur in several of the streams in this area.

Doma, the central part of the Doma Peaks complex, straddles the probable location of the southeast part of the Lema-Ambua crater wall. It consists of extremely rugged, forest-covered ridges separated by almost vertical-walled ampitheatre-headed valleys up to 800 m deep. There are at least two deep craters; these are at the head of the north branch of the Huria River. The U-shaped scarp at the head of the Toma River may also be an eroded crater, as it seems too large and smoothly curved to be simply the head of an ampitheatre-headed valley. Part of the central complex has been buried by the Huria River flows.

Satellite cones and domes are located on the northeast flank and on the southern flanks. A small cone, with a summit crater, and an elliptical dome about 100 m high are situated close to the intersection of two fault systems on the northeast flank. A small raised crater with a crater lake lies next to one of the faults about 2 km to the north. The two cones with eroded craters on the southern flank are about 150-200 m high, and the domes to the west are about 80 to 100 m high. The southern pair of domes is situated close to a series of low escarpments which may be of volcanic origin.

Mount Ne (3000 m above sea-level) is a forested ridge situated on the smoothly sloping saddle between Doma Peaks and Mount Kerewa to the south (Fig. 15). The main ridge shows no distinctive volcanic features, and

FIGURE 12 GEOLOGY OF DOMA PEAKS AND MOUNT NE



TOPOGRAPHIC DETAIL (DRAINAGE AND CONTOURS) FROM DEPARTMENT OF NATIONAL DEVELOPMENT, DIVISION OF NATIONAL MAPPING'S "DOMA PEAKS SPECIAL, PAPUA"

CONTOUR INTERVAL 100 METRES

To accompany Record 1973/89

B54/A8/22

Figure 13. Summit and part of eastern crater wall, Doma Peaks, looking north. The survey marker can just be made out at the top of the steep scarp. Neg. GA/5444.

Figure 14. Crater area and lahar from eastern crater wall, Doma Peaks. The northern scarp of the central complex, Doma, is at left, and the Ambua scarp is on the right. Beyond the Arua gorge is the Tari valley. Neg. GA/5450.

appears to have been partly buried by the volcanic products of Doma Peaks and Mount Kerewa. Its northern side is roughly scarp-like and much steeper than the southern side; it may be an eroded portion of a crater wall. On its southeastern flank are two elliptical structures, one of which may be a cumulodome, the other resembling a crater.

Volcanic History

The escarpments in the headwaters of the Piwa River and along the southern side of the headwaters of the Huria River probably represent the remains of the earliest phase of activity which culminated in the formation of a caldera. The slopes and satellite domes and craters northeast and south (respectively) of these scarps also belong to this earliest phase. Ambua scarp and the ridges to the north, and Lema scarp and the slopes to the east, represent the next phase. A large crater developed on the eastern side of the old caldera during this phase. The central Doma complex followed, possibly on the outer rim of the crater, or straddling the crater wall which had been eroded back. During or just after the Doma phase, the main crater was breached in at least two places, on the northeast and southwest sides, and further activity from the crater spilled flows through these gaps. The flows which poured through the southwest gap partly buried the Doma complex, the crater wall, and the old caldera escarpment. A period of erosion followed during which the Arua River breached the main crater and extensive outwash deposits were laid down in the Tari valley. Renewed activity in historic times produced the lahar at the base of Lema scarp, and probably also avalanches and nuées ardentes which moved down the Arua gorge and stripped off the vegetation along each side. It also produced the legends about the 'Bingi' (gods of the mountain) reported by Glasse (1963).

Present and recent activity is confined to solfataras and thermal areas (see also Cooke, in prep.). Active solfataric areas are marked with an 'S' in Fig. 12; one which is cold and inactive, and another which was extinct or nearly so in 1968 are marked '(S)'. Taylor noted dead trees, sulphur being deposited on moss-covered ground, a strong H_2S smell, and highly altered rocks just north of point 0012 (Fig. 12). In 1971 it was noted that another similar area nearby (point 0012) was completely inactive. Another inactive area about 300 m west, next to a small lake, was characterized by a lack of vegetation and some iron-staining; it was also inactive in 1968.

Farther south at the base of the bluff below point 0009, where Taylor noted dead trees in 1968, is a group of three solfataras or springs. One is cold, encrusted with sulphur, and smells of H_2S. The other two are cold, vigorously bubbling aqueous springs which deposit colloidal sulphur, and smell strongly of H_2S. About 200 m south, at the mouth of a small gully, is an area noted by Taylor as being boggy and moss-covered, with pools and springs of cold water which bubbled vigorously and deposited colloidal sulphur. The area smelled strongly of H_2S, and vegetation was severely inhibited. Chemical tests showed the water to contain an appreciable amount of free sulphuric acid, but no chlorides. Similar springs occur on the southern side of the gully mouth. These springs were unchanged when re-examined in 1971.

A small spring which smells of H_2S and has produced a white to blue-grey crust on the surrounding rocks is located at point 0008, near the mouth of the deep gully immediately west-southwest of the summit. Near the head of this gully, at point 0001, there is an area of cold springs depositing red-brown iron oxides and sulphur, and smelling of H_2S. Pyrite is common in or on the rocks in this area. Nearby is a hollow about 8 m wide and 0.8 m deep in which all the vegetation below the lowest point of the rim is dead. Timber has been bleached, and the hollow is filled by a colourless dense gase, probably SO_2, which is extremely irritating to the eyes and lungs, and does not burn or support combustion.

Other springs occur at point 0005, on the northern side of the lahar, and on the bank of the Arua River about 500 m downstream from the nose of the lahar. At the first locality, Taylor (1971) noted cold springs similar to those near point 0009, and in 1971 highly altered rocks were noted in the area. The spring in the Arua River is tepid and has deposited iron compounds on the rocks. Another group of three springs occurs farther upstream near point 0210-13; these are warm (32-35°C) aqueous springs depositing orange-red colloids.

GEOLOGY

Doma Peaks

Only three areas of Doma Peaks were examined in detail - the eastern crater wall (Lema) and crater floor area, the lower Arua gorge, and the head of the Toma River (Fig. 12). Therefore the detailed geology of the complex is not known; however, it is possible to make the following conclusions.

The Doma Peaks complex is made up predominantly of 2-pyroxene andesite and hornblende-2-pyroxene andesite, some of which contains a little olivine. These occur mainly as thick lava flows; pyroclastic deposits, agglomerates, and lahars are uncommon in the crater area, but are increasingly common towards the flanks. Massive volcanic rudites are exposed in the lower Arua gorge, and massive ash-flow or lahar deposits with boulders up to 1 m across are exposed in the head of the Toma River. In many places, especially around the springs and solfataras in the crater area, the rocks are encrusted with sulphur, or pyrite, or both, or are extensively hydrothermally altered. Some rocks in the crater area also contain disseminated pyrite.

There are noticeable differences in the lithologies present in the three main areas examined. The central complex (Doma), which is made up of olivine basalt, 2-pyroxene andesite, and minor olivine-2-pyroxene basalt and hornblende-2-pyroxene andesite. Rocks with appreciable amounts of olivine are rare in the other parts of the Doma Peaks complex.

The eastern crater wall (Lema) is made up predominantly of thick flows of olivine-bearing 2-pyroxene andesite which generally contains some hornblende or biotite, or both. Two-pyroxene andesite is also present. Rocks from the crater floor area include olivine-2-pyroxene andesite, 2-pyroxene andesite and some hornblende-bearing andesite, some of which contain olivine and biotite.

Ambua scarp and the lower Arua River gorge are made up predominantly of hornblende-pyroxene andesite, with minor olivine-bearing (2-pyroxene) basalt. Rocks with more than a trace of hornblende are rare in the other parts of the complex that were visited.

Mount Ne

Specimens of 2-pyroxene andesite and hornblende-2-pyroxene andesite were collected from float in a stream on the western side of Mount Ne. They are similar to andesites in the crater area of Doma Peaks.

Pre-Doma Rocks

The rocks underlying and surrounding the Doma and Ne volcanic rocks are dominantly folded Miocene limestones, with minor Upper Cretaceous and upper Miocene shale and marl. No appreciable influence seems to have been exerted on the volcano by either the underlying topography or subsequent movements.

PETROGRAPHY

Doma Peaks

The olivine basalts (or shoshonites) from the Doma (central) complex consist of abundant large plagioclase phenocrysts (up to 1.5 cm long), smaller, less common augite and olivine phenocrysts, and generally a few magnetite microphenocrysts in a groundmass of plagioclase laths, augite prisms, tiny magnetite euhedra, a little interstitial potash feldspar, and accessory apatite. One rock, from the Toma River (0219), contains about 5 percent hypersthene and 3 percent interstitial glass in the groundmass. Plagioclase (63 to 75%) in these rocks forms phenocrysts from 0.3 to 15 mm long (generally about 1 to 3 mm), and 0.01 to 0.1 mm long laths in the groundmass. The phenocrysts are strongly zoned and charged with fine-grained groundmass inclusions; in some rocks they have narrow potash feldspar rims. In some rocks the plagioclase is partly altered. Augite (10 to 20%) occurs as small prisms in the groundmass, and in most rocks as rare to moderately abundant phenocrysts from 0.2 to 3 mm long. In the rock from the Toma River, the augite is pale yellow-green in colour and occurs in the groundmass only; it is probably oxidized. Olivine (3 to 7%) forms phenocrysts 0.3 to 2 mm long, and a few groundmass crystals 0.01 to 0.2 mm long. In the Toma River rock, it occurs as small, equant crystals generally 0.05 to 0.1 mm across, rarely up to 0.4 mm. In most of the rocks it is slightly to almost completely replaced by bowlingite, opaques, and some calcite.

The olivine-bearing 2-pyroxene basalts and andesites grade into olivine basalt and shoshonite with increasing amount of olivine and decreasing hypersthene. They consist of plagioclase, augite, hypersthene, and olivine phenocrysts in order of decreasing abundance, rare magnetite microphenocrysts, and a moderately fine-grained, generally holocrystalline groundmass of plagioclase, augite, hypersthene, magnetite, a little potash feldspar, and accessory apatite. Olivine occurs in the groundmass of several rocks, and a few contain up to 10 percent interstitial glass. Trace to minor amounts of biotite (light yellow-brown to extremely dark brown, reddish yellow-brown, or deep red-brown), or of basaltic hornblende, or both occur in some rocks from the crater wall and rim (0002, 0005, 0011, 0012, 0028. 0029, 0030). Some rocks contain only small amounts of olivine or hypersthene, and lack hypersthene phenocrysts.

Plagioclase (55 to 80%, generally about 70%) occurs as phenocrysts 0.2 to over 5 mm long (generally 1-2 mm) with strong normal and oscillatory zoning and inclusion-rich cores or zones. Many of the larger phenocrysts have large, inclusion-filled calcic cores with patchy extinction, and clear, narrow rims with oscillatory zoning. Groundmass laths are up to about 0.1 mm long, weakly to strongly normally zoned, and of andesine composition.

Augite (10 to 20%) forms very pale brown or green-brown phenocrysts, generally about 0.5 to 1 mm long, but ranging between 0.1 to 2, 3, or even 4 mm long. They are commonly clumped together, with or without hypersthene or olivine. The groundmass crystals are colourless to pale green or yellow-green, and generally about 0.01 to 0.05 mm long.

Hypersthene (2 to 20%; generally 10 to 15%) forms elongated prismatic phenocrysts (0.2 to 2.5, generally 0.5 to 1.0 mm long) and groundmass crystals. It is commonly mantled by augite, clumped with augite, or in rims on olivine; less commonly it forms irregular cores in augite phenocrysts. It is weakly to moderately pleochroic in shades of pale green and **faint pink to pale red.**

Olivine forms pyroxene-rimmed phenocrysts up to 3 mm long (generally about 0.5 to 1.5 mm), and rare smaller groundmass grains. It is commonly partly to completely altered to combinations of bowlingite (chlorite and iron oxides), iddingsite, serpentine, calcite, talc, and opaques. The pyroxene rims range from extremely narrow (less than 0.01 mm) to complete replacement of the crystals. In many rocks, some of the olivine is clumped with augite, or augite and hypersthene.

Magnetite (2 to 7%) forms small (0.1 to 0.4 mm) microphenocrysts which are commonly clumped with or included in pyroxene and olivine phenocrysts, and small (0.01 mm) euhedral groundmass crystals. It is generally monomineralic titaniferous magnetite, but in some rocks contains a little intergrown or exsolved ilmenite.

Potash feldspar (trace to 3%; absent in a few rocks) occurs interstitially in the groundmass, and, in some rocks, as narrow rims on plagioclase phenocrysts and microphenocrysts.

The 2-pyroxene andesites are made up of abundant (10 to 35%) plagioclase phenocrysts, augite and, generally, hypersthene phenocrysts, and a fine-grained groundmass of plagioclase, augite, hypersthene, magnetite, a little potash feldspar, and accessory apatite. A few rocks contain traces of olivine; one of these (0027 from the summit ridge) also contains a little hornblende which is largely replaced by pyroxene and magnetite, a trace of biotite, and a few interstitial patches of tridymite. Hornblende also occurs in two rocks from the Toma River (0222, 0224). Minor amounts of interstitial glass occur in several rocks, but one, from the head of the

Arua River (0207) is an oxidized vesicular lava with a 30 percent dark yellowish-brown glass. There is a trace of tridymite in a rock from the cliffs at the head of the Toma River (0215).

Plagioclase constitutes 60 to 80 percent of most of these rocks, but only 40 percent of the glassy lava, 0207. It occurs as weakly to strongly zoned phenocrysts 0.2 to 6 mm, generally averaging about 1 mm long, and 0.001 to 0.1 mm long groundmass laths. The phenocrysts are generally rich in inclusions of fine-grained dark groundmass or glass, and commonly have well defined calcic cores with patchy extinction, and clear rims with oscillatory zoning. Their composition ranges from calcic andesine-labradorite or even bytownite in the cores to andesine or oligoclase in the rims. Groundmass crystals are probably andesine or oligoclase.

Augite (5 to 17%) forms small (0.2 to 1.3, av. 0.4-0.6 mm) to large (up to about 2.5 mm) phenocrysts, and equant granules (0.01 to 0.05 mm) and microlites in the groundmass. It is faint brown or brown-green and the phenocrysts are commonly clumped or composite. A few phenocrysts have cores of hypersthene, and augite forms rims on hypersthene in some rocks.

Hypersthene (1 to 20%) occurs as tiny groundmass prisms and needles, and in most rocks as phenocrysts similar in size to the augite phenocrysts. The phenocrysts are euhedral prisms, commonly elongated, and usually contain small irregular inclusions and minute lenticular exsolved blebs of clinopyroxene in their cores. **Partial or complete rims of augite are common.** In oxidized rocks, the hypersthene is stained red-brown, but in most rocks it is pleochroic from faint green to pale pinkish red.

Magnetite (2 to 7%) forms small microphenocrysts or irregular clumps of microphenocrysts, commonly clumped with pyroxene, and tiny euhedral crystals in the groundmass. It is titaniferous, and contains some ilmenite.

Olivine (0 to 2%), where it occurs is rimmed and partly replaced by pyroxene or magnetite, and is generally largely to completely altered to chlorite or bowlingite and calcite.

Hornblende (traces only) is yellow-brown and largely replaced by fine-grained pyroxene and magnetite, with or without plagioclase.

Tridymite (trace to 1%) occurs as small patches of wedge-shaped or polygonal crystals in the groundmass and, rarely, in plagioclase phenocrysts.

Apatite, as in most of the other Doma Peaks rock types, occurs as small (up to 0.1 or 0.2 mm) clear or pleochroic brown prisms. The brown crystals commonly have darker brown or black margins, and owe their colour and pleochroism to minute inclusions of a red-brown near-opaque mineral (hematite?) aligned parallel to the **'C' (long) axis. Apatite is commonly** included in or clumped with ferromagnesian or opaque minerals.

The hornblende-2-pyroxene andesites, which come mainly from the lower Arua gorge and the head of the Toma River, are similar to the 2-pyroxene andesites but contain a trace to 7 or 8 percent of hornblende. Plagioclase makes up 60 to 75 percent, augite 7 to 17 percent, hypersthene

3 to 12 percent, and magnetite 3 to 7 percent of the rock. Potash feldspar is present in trace or minor amounts in some rocks; tridymite is rare. Apatite is a ubiquitous accessory mineral. The hornblende occurs as phenocrysts 0.1 to 3.7 mm long, averaging 0.5 to 1.0 mm long, and rare smaller crystals. Fine-grained pyroxene and magnetite forms narrow to broad rims on the hornblende, or in a few rocks, largely to completely replaces it. In a few rocks, the rim is missing. Pleochroism is:

α = (very) pale yellow-brown

β = greenish yellow-brown, deep yellow-brown, or deep reddish brown

γ = dark greenish to yellowish brown, yellowish green, brownish green, or deep red-brown to pinkish red-brown.

Some zoning is evident, particularly in sections parallel to the long (c) axis. It is a basaltic hornblende in various stages of oxidation, the most oxidized being the variety showing strong red colours and lacking green.

At locality 0208, in the head of the Arua River, the outcrop is very dark grey porphyritic andesite which is made up of large (up to over 5 mm) relict plagioclase phenocrysts (20%) in a recrystallized groundmass of small, equant euhedral to rounded augite crystals (15%), matted clumps of biotite (5%) with interleaved chlorite (1%) and muscovite (trace), recrystallized plagioclase (54%), and opaques (5%). The relict phenocrysts are marginally granulated, or recrystallized, or both. The biotite is pleochroic from green to deep red-brown. The rock has been sheared and partly metamorphosed.

Mount Ne

The andesites from Mount Ne consist of phenocrysts of plagioclase (1 to 4 mm), augite (0.5 to 2.2 mm), hypersthene (0.5 to 1.4 mm), and in one rock some hornblende (0.1 to 3 mm), in a groundmass of plagioclase, augite, hypersthene, magnetite, a little potash feldspar, and accessory apatite. Magnetite also occurs as 0.1 to 0.3 mm microphenocrysts. Estimated mineral percentages are: plagioclase 68 to 75 percent, augite 8 to 15 percent, hypersthene 6 to 12 percent, magnetite 5 to 7 percent, and potash feldspar a trace to 2 percent. There is 2 percent (originally 5%) yellow-brown basaltic hornblende, largely replaced by magnetite and pyroxene in one rock.

DISCUSSION

The lavas of Doma Peaks and Mount Ne are dominantly 2-pyroxene andesites and hornblende-2-pyroxene andesites, many of which are olivine-bearing. They are probably high in potash (over about 2% K_2O), and many are low-silica types. However, the basic, highly potassic olivine-rich lavas, or shoshonites typical of most other Highlands volcanoes are almost entirely lacking. The common occurrence of small amounts of relict olivine suggests that the rocks were derived from a more olivine-rich parent, perhaps a shoshonitic magma which was trapped and fractionated at some depth below the volcanoes. The continued solfataric and hydrothermal activity indicates that this body of magma may still be hot and producing sulphurous liquids and gases. The presence of pyrite mineralization in lavas now at the surface suggests that mineralization may be more intense at depth, and could involve metals other than iron. Only minute traces of copper sulphides were found in the exposed lavas.

MOUNT KEREWA

GEOGRAPHY

Mount Kerewa (Fig. 15) is about 10 km south of Doma Peaks and 30 km southeast of Tari. Komo patrol post, which BP Petroleum Development of Australia used as a base for their Mananda well, is 40 km to the west. There is a small airstrip at a mission on the banks of the Benari (or Nari) River, on the southwest flank of the Kerewa range, and there are several small villages in this area and farther west. Small villages are also located in some of the other flat-floored gorges southwest and south of the range.

Access to the mountain is by foot, or by helicopter. Landings can be made in many places along the grassy summit ridge, on grassy areas at the foot of the northern end of the mountain, and in villages along the southwestern and southern gorges. It is also possible to land a helicopter on a small arcuate grassy area below the crater wall (Fig. 15).

MORPHOLOGY

The Kerewa range, of which Mount Kerewa (about 3700 m above sea level) is a part (Fig. 15), is a rugged to extremely rugged ridge shaped in plan like an inverted J, with the shaft portion pointing south, and a 300 to 800 m high escarpment on the concave side. The crest of the ridge is jagged and rocky to smoothly knobby, and covered with tussocky grass, small bushes, and patches of bracken. Some of the ridges radiating from the summit ridge, particularly at the northern end, are similarly capped at their higher ends. The escarpment (Fig. 15) is generally smoothly curved and slopes at 50° to 75°. At its northern end it is deeply embayed by one large and several smaller ampitheatre-headed valleys. Partly enclosed by the escarpment is an area of very subdued forested topography drained by the Benari River. This area is dominated by a low, rounded hill (Fig. 16) which is elliptical in plan. A narrow, partly grass-covered valley parallel to the escarpment separates it from this hill (Fig. 16). The western side of this valley may mark the position of the foot of the original crater wall, and the hill may represent the old crater floor, which was possibly a dome, or a later dome. The northwestern, northeastern, and eastern sides are deeply dissected by steep V-shaped valleys which coalesce downslope and finally change into small, near-vertical-walled gullies. The northwestern flank is rather sharply truncated by a probable fault along the northern branch of the Benari River. The lower western slopes and apron are smooth and gently sloping, cut only by the broad cultivated valley of the Benari River, and numerous small gullies. In complete contrast, the southern flanks are very deeply dissected into a series of winding, precipitous gorges, high cliffs, and flat to round-topped ridges. All the slopes except the upper slopes on the northern and northeastern sides are densely forest-covered.

Because the only airphotos of the crater area of Mount Kerewa are largely cloud-covered, it was not possible to produce a map of this volcanic centre.

GEOLOGY

The central crater area of Mount Kerewa is made up of pyroxene andesite, much of which is hornblende-bearing, and rare olivine basalt. They occur in thin flows, the edges of which are clearly exposed in the eroded crater wall (Fig. 16), and over much of the grassy summit ridge and upper parts of the adjoining ridges on the flanks. More than 20 successive flows were counted at one place on the central part of the crater wall.

On the northwest flank, near the north branch of the Benari River, massive andesitic lava flows are overlain by partly consolidated boulder conglomerate, which is probably old outwash. In the south branch of the Benari River, outcrops are of strongly jointed non-porphyritic lava, and weathered volcanic rudite or agglomerate.

On the crater floor, specimens of coarsely porphyritic plagioclase-rich andesite were collected from talus heaps at the base of the escarpment and at the foot of the central hill. A few kilometres west of the probable fault along the north branch of the Benari River is a group of small cones, craters, and domes on or close to a strong east-west lineament. There is a distinct arcuate lineament with a 1 km radius associated with the westernmost pair of small craters; it resembles part of a ring fracture. Four kilometres north is a small, deeply eroded volcanic remnant about 100-120 m high which may be the same age as Mount Ne.

Pre-Kerewa Rocks

Complexly, but generally gently or moderately folded middle Miocene limestone, with some younger shale and marl, and rare inliers of Upper Cretaceous shale and siltstone underlie and surround the Kerewa volcanic rocks. The underlying topography and geology do not appear to have had any marked effect on the volcano's form.

PETROGRAPHY

The lavas of Mount Kerewa are 2-pyroxene andesites, most of which contain some hornblende, and a few some olivine. One rock from the northern summit area is an olivine-2-pyroxene high-K basalt. The olivine-bearing andesites and the other more basic andesites also come from this area, and from the crater floor area and the Benari River which drains it. The more siliceous, mafic-poor lavas come from the northwest flank.

Figure 15. Mount Ne and Mount Kerewa from the eastern side of Doma Peaks. Neg. GA/5459.

Figure 16. Part of 'crater' wall and 'crater floor' area, Mount Kerewa, showing numerous flows exposed in the wall, the central hill (left) and grassy area referred to in text. Neg. GA/5449.

The andesites consist of abundant (15 to 20%) large phenocrysts of plagioclase up to 2.5, 3, or even 5 mm long, and smaller, less numerous augite (1-8%), hypersthene (trace to 7%), and commonly hornblende phenocrysts (1-5%) in a fine-grained dark groundmass. A few rocks contain a little relict olivine as small phenocrysts with pyroxene rims. The groundmass is made up of plagioclase laths, small augite and hypersthene prisms, magnetite, generally a little potash feldspar, and accessory apatite. Some rocks have a trace to 1 percent of tridymite as small patches in the groundmass; a few contain a similar amount of groundmass hornblende. Interstitial pale brown or pinkish-brown glass forms 15 percent of one rock from the crater wall, and 5 percent of an acid (high-silica) andesite from the northwest flank.

The olivine basalt from the northern crater rim consists of plagioclase, augite, hypersthene, and altered olivine phenocrysts (5%) in a moderately fine-grained groundmass of plagioclase, augite, hypersthene, magnetite, potash feldspar, accessory apatite, and about 5 percent of interstitial light pinkish-brown glass. The olivine is completely altered to talc(?) and chlorite, and has narrow hypersthene rims.

The strongly jointed non-porphyritic lava from the Benari River, near Egeanda village, is a flow-banded pyroxene dacite or high-silica andesite consisting of rare, small phenocrysts of plagioclase (trace to 1%) and augite (trace) in a very fine-grained, strongly flow-aligned groundmass of plagioclase laths (77%), augite and hypersthene (10%) in about equal quantities, magnetite (7%), potash feldspar (3%), tridymite patches (1-2%), and a trace of apatite. Another rock from the Benari River is a hornblende-2-pyroxene andesite heavily altered to chlorite and calcite.

<u>Plagioclase</u> in the Kerewa lavas makes up to 60 to 75, generally 65 to 70 percent of the rock. It forms small to large (0.3 to 5 mm) phenocrysts with strong normal and weak to strong oscillatory zoning. Most phenocrysts have narrow to broad zones or cores packed with minute dark inclusions, or contain a few, larger scattered inclusions of pyroxene, or fine-grained groundmass. The groundmass laths are weakly to strongly normally zoned.

<u>Augite</u> (10 to 20%) occurs as small to medium sized (0.2 to 1.5 or 2 mm, rarely 3 mm) phenocrysts which have a moderate tendency to clump together, with or without hypersthene, plagioclase, or, rarely, olivine. Some phenocrysts have cores of hypersthene; a few have olivine cores. Augite also forms small euhedral prisms in the groundmass, and, in some rocks, narrow rims on some of the hypersthene phenocrysts.

<u>Hypersthene</u> (7 to 15%) forms prismatic phenocrysts, commonly with rounded corners, from 0.2 mm to 1.5, 2.0, or even 2.5 mm long, but averaging 0.4 to 0.8 mm long, and very small elongated prisms and needles in the groundmass. It also occurs as rims on olivine. The phenocrysts commonly contain small rounded inclusions of augite and plagioclase, and most contain minute clinopyroxene exsolution lamellae in their cores; some smaller ones have augite rims. The hypersthene is strongly pleochroic from pale green to light pinkish red.

Hornblende (up to 3, originally 5%) occurs as generally small (0.4-0.6 mm) phenocrysts, but some are up to 1.5, 2.5, or even 3.5 mm long. It is rimmed or variably replaced by fine-grained pyroxene, magnetite, and possibly plagioclase. Smaller phenocrysts are commonly largely to completely replaced. It is pleochroic in the colours

α	β	γ
very pale yellow-brown	greenish-brown	green
pale yellow-brown	green-brown	brownish-green
" " "	deep yellowish-brown	deep yellowish-brown
very " " "	slightly greenish dark yellow-brown	
" " "	yellow-brown	yellowish green
very pale brown	greenish yellow-brown	green-brown

Thus it is a basaltic hornblende, less green in the more oxidized types.

Magnetite (2 to 7%) forms small (0.1-0.3 mm) microphenocrysts (trace to 2%) and minute euhedral crystals in the groundmass. The microphenocrysts have a strong tendency to be clumped with or included in pyroxene or hornblende phenocrysts.

Olivine (trace to 5%) occurs as small relict phenocrysts rimmed by pyroxene. It is commonly partly to entirely altered to chlorite, talc, opaque minerals, and calcite.

Potash feldspar (trace to 1, rarely 3%) forms extremely narrow rims on plagioclase crystals and minute interstitial patches in the groundmass of holocrystalline rocks.

Tridymite (up to 2%) occurs as very small (up to 0.3 mm) patches of polygonal or wedge-shaped grains in the groundmass.

DISCUSSION

The lavas of Mount Kerewa are petrographically similar to and probably originated in the same way as the Doma Peaks lavas.

MOUNT BOSAVI

GEOGRAPHY

Mount Bosavi (Fig. 17) is situated at the western end of the Darai Hills-Leonard Murray Mountains range, the southernmost foothills of the Southern Highlands. To the west and south are the slightly to moderately dissected Fly-Strickland plains, and to the north is a high limestone ridge culminating in Mount Sisa, another Quaternary volcano. It is 55 km south of Komo patrol post, the nearest administrative centre and public airstrip. Bosavi Asia-Pacific Christian Mission, which has an airstrip suitable only for light aircraft in dry weather, is on the lower northern slopes of the volcano. There are moderately large cultivated areas and several villages

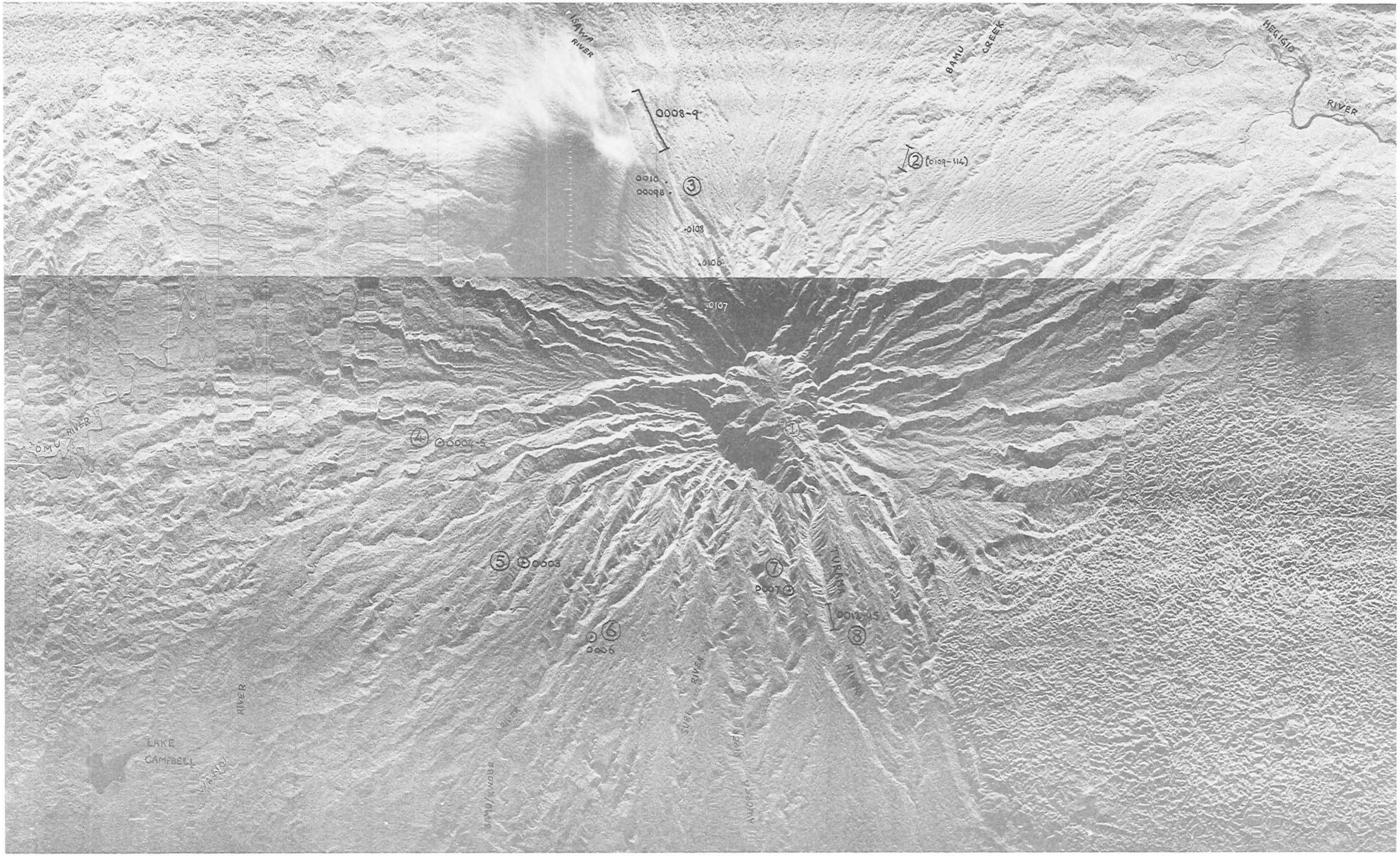


Figure 17. Radar imagery of Mount Bosavi, showing localities sampled. Centre strip may appear to have inverted relief because the radar beam was directed from the south; it also shows some electrical distortion on its left side. White patch and shadow near Isawa River is due to heavy rain. Imagery by Westinghouse-Raytheon for Department of the Army. Approximate scale 1:240,000.

in the vicinity of Bosavi Mission, and to the west and north. A track runs from the mission to the northern crater rim, and several tracks connect the villages in the area with each other and with the few scattered villages around the lower flanks of the mountain (mainly on the southern side). It is possible to walk around the volcano via these villages in 3 or 4 days. Helicopter landings can be made at many places in rivers around the lower flanks, in villages, in and around which are the only areas devoid of dense rainforest, and in one or two places on the Turama River within the crater.

MORPHOLOGY

The almost perfect conical form of Mount Bosavi, with its equally perfect radial drainage (Fig. 17) is sharply truncated about 2000 m above its base (Fig. 18). It culminates in a roughly circular summit ridge which has an extremely steep and rugged scarp-like inner face up to 1200 m high, and is broken by the huge V-shaped gorge of the Turama River on its southeastern side. The summit ridge represents the original summit crater, which has been greatly enlarged by internal erosion along short but extremely deep and steep-sided ampitheatre-headed valleys. Radiating from the summit-ridge, or crater rim, are V-shaped gorges up to 500 m or more deep. Most of these gorges notch the crater rim either through their own headward erosion or through intersection by the outwardly eroding crater wall. The gorges become shallower and broader downslope, then narrow again on the gently sloping apron to almost vertical-walled ravines. On the eastern side, where the volcanics overlie limestone, most of the gorges become greatly enlarged where the streams have cut through to the limestone. This is probably due to rapid undercutting of the volcanics by removal of the more rapidly eroded and soluble limestone. On the northern flanks, the main ravines are widely spaced and separated by broad, roughly triangular planezes which have a smooth constructional surface cut by numerous narrow gullies. Planezes on the eastern and western flanks are narrower, and cut by larger, broader stream valleys. The radiating gorges on the southern side are larger than the others and so close together that many of them intersect; planeze remnants are rare.

When viewed in profile (Fig. 18), Mount Bosavi can be seen to be the stump of an originally very much larger and higher volcano. If the present slopes are projected upwards to produce a shape concordant with active stratovolcanoes in other parts of Papua New Guinea, they form a cone between 3800 and 4400 m high (Fig. 19). It is possible that continuous erosion of the summit area and crater during the active life of the volcano prevented it from ever reaching such heights, but the size of the gorges on the outer rim of the present eroded crater indicates that the cone was much higher than it is now.

Scattered over the slightly dissected plains to the southeast of the mountain are lines and clusters of small conical and dome-like hills, craters, and caldera-like depressions. The most remote of these is 80 km from the crater of Mount Bosavi. Most of these hills and craters lie on or very close to parallel south-southwesterly trending lineaments. They are surrounded by areas of lava which produce a smooth texture on the airphotographs and radar imagery.

GEOLOGY

Mount Bosavi is a stratovolcano with a cone made up of lava, agglomerate, and pyroclastic deposits, and lower slopes and apron composed of pyroclastic deposits, outwash, lahar deposits, lava, and agglomerate. The amount of lava and agglomerate decreases while the other material, particularly outwash, increases in abundance away from the central crater. The lavas are dominantly coarsely porphyritic olivine basalts, some containing a little hypersthene, and a few a trace of hornblende, with associated minor hornblende-bearing andesites.

The crater area appears to be composed mainly of lava, though no obvious flows are exposed in the walls. There are extensive areas of bleached rocks, and some prominent yellow patches which are probably sulphur; these may indicate recent hydrothermal and solfataric activity. Outcrop at the helicopter landing site in the Turama River (locality 1, Fig. 17) is altered olivine basalt, and float in the stream includes olivine basalt, hornblende andesite, partly altered olivine basalt, metamorphosed basalt, volcanolithic grit, and a leucocratic pyroxene-hornblende microdiorite.

Outcrop at localities visited on the lower flanks is generally gently dipping thin to thick-bedded volcanolithic sandstone, grit, or rudite, with intercalated lava and weathered pyroclastics. Lava outcrops are scarce and generally weathered, so most specimens were collected from float. In the eastern branch of Bamu Creek, on the northeast flank (locality 2, Fig. 17), exposures include well cross-bedded volcanolithic grit and intercalated pebbly sandstone in beds up to 3 m thick, and basaltic lava flows up to 10 m or more thick. At one locality, there is at least 100 m of bedded grits overlain by about 10 m of lava. The upper 2 m of grit is bright brick red, and resembles a soil horizon, while the lower part of the lava flow is a purple or violet colour due to the presence of hematite. About 1 km upstream, a massive olivine basalt flow with a vesicular top overlies fine-grained brown volcanolithic sediments. A few hundred metres downstream from the first locality, conglomeratic sandstone with subangular to subrounded lava clasts 2 to 15 cm across is overlian by 3 m of cross-bedded gritty volcanolithic sandstone, then another bed of conglomeratic sandstone, and finally a 1 m bed of brownish laminated gritty clay, or tuff.

On the northwestern flank, in the headwaters of the Isawa River, a tributary of the Rentoul River (locality 3), the outcrop is mainly bedded volcanolithic arenite grading into coarse rudite. Some outcrops of hornblende-bearing olivine basalt and hornblende andesite occur near a small satellite cone which is situated between the two main branches of the Isawa River.

In the upper reaches of the Tomu River, on the lower western flanks (locality 4), the outcrops are bedded earthy volcaniclastic deposits with layers enriched in lava boulders, and massive olivine basalt lava. Horizontally bedded volcanolithic arenite up to 30 m or more thick crops out in the headwaters of the Wawoi River, 7 km to the south (locality 5), in the upper reaches of a western tributary of the Bamu River, 5 km farther to the southeast (locality 6), and the first gorge west of the Turama River,

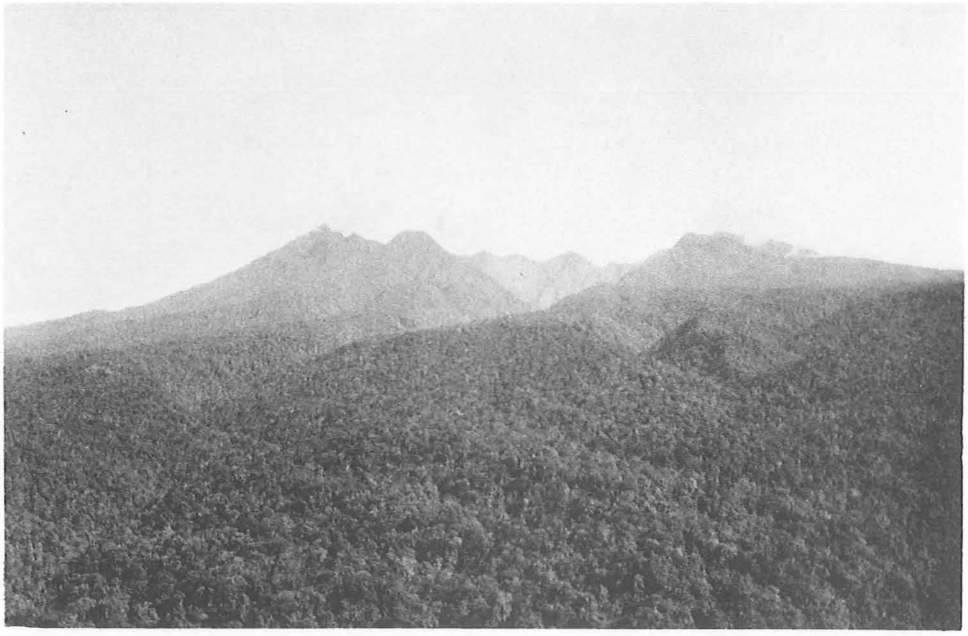


Figure 18. Mount Bosavi from the southeast, near the Turama River (at left). Part of the inner eroded crater wall can be seen through the deep notch of the Turama gorge.
Neg. GA/5462.

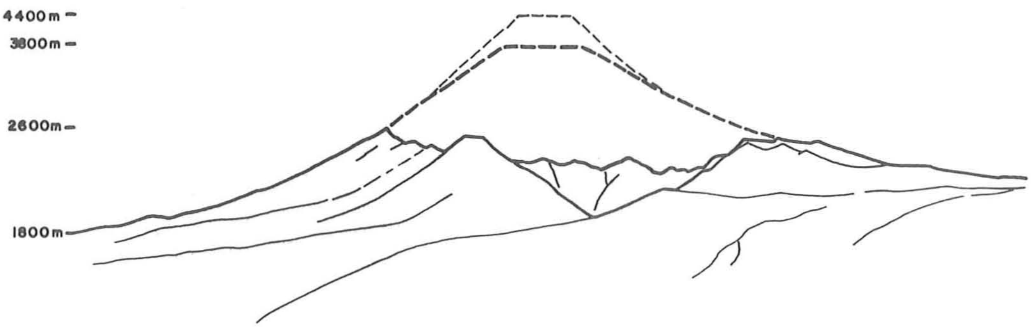


FIGURE 19 RECONSTRUCTION OF MOUNT BOSAVI (lower alternative is favoured)

7 km south of the crater rim (locality 7). Outcrop in the lower Turama gorge (locality 8), includes massive volcanolithic arenite, olivine basalt flows, and intercalated volcanolithic arenite (containing some large lava boulders) and rudite.

Float at all these localities is dominantly dark grey to almost black porphyritic olivine basalt, with rare to minor hornblende andesite. Andesite is most abundant in float in the Turama River; it probably originates from the crater area.

Geologists of the Australasian Petroleum Company (1961) reported that in the crater walls there is a sequence from olivine basalt, through 300 m of fine basaltic agglomerate, to hornblende andesite 90 to 150 m thick at the top. This is in accordance with our observations but it was not verified.

Pre-Bosavi Rocks

A broad anticline of middle Miocene limestone plunges beneath the eastern side of Mount Bosavi. A large thrust fault, with north side upward, which marks the northern boundary of this limestone block also cuts off the northern apron of the volcano. Underlying and interfingering with the Bosavi volcanic rocks on the southern and western sides are Pliocene to Quaternary terrestrial sediments. Much of the Quaternary sediment is derived from Mount Bosavi itself. The sediments are largely volcanolithic arenite, with lesser rudite and lutite.

The gradation of the Bosavi volcanic rocks into the surrounding derived sediments makes delineation of the volcanics difficult, if not impossible.

PETROGRAPHY

The lavas of Mount Bosavi can be divided simply into two main groups: basic to siliceous shoshonites (or high-K olivine basalts) (43 specimens) and hornblende andesites (16 specimens). There are also a few highly altered or metamorphosed rocks (3 specimens) from the crater area.

Shoshonites

The shoshonites contain between 20 and 52 percent ferromagnesian minerals; the most basic ones may be absarokites. They consist of abundant plagioclase phenocrysts, generally 0.5 to 1 mm long, less abundant but larger augite and olivine phenocrysts, and in most rocks some magnetite microphenocrysts, in a groundmass of plagioclase, augite, a little olivine, magnetite, potash feldspar, and accessory apatite. Hypersthene (trace to 4%) forms small needles in the groundmass, or cores in augite phenocrysts, or both, in about a third of the rocks. Trace amounts of hornblende, or biotite, or both, are present in a few of the shoshonites. Quartz xenocrysts were found in three specimens. Alteration, due either to weathering or other agencies, is very common, affecting particularly the olivine; chlorite and calcite are the most common secondary minerals.

Plagioclase in the shoshonites makes up 40 to 70 percent of the rock, generally around 60 to 65 percent. The phenocrysts (2 to 6%, generally about 20%) vary from 0.2 to more than 3 mm, averaging between 0.4 and 1 mm long. They are generally strongly zoned with oscillatory zoning superimposed on an overall normal zoning, and contain abundant zoned inclusions of either fine-grained dark groundmass or larger single grains of pyroxene, etc., or both. Some phenocrysts are composite, and some are clumped together with or without pyroxene and olivine. Compositions are in the range bytownite (cores) to andesine (rims). Groundmass plagioclase is generally in lath form, with moderate normal or oscillatory zoning, and is generally in the andesine compositional range.

Augite (15 to 30, rarely 40%) forms small (0.2 to 1.5 mm) to large (up to 6 or 7 mm) phenocrysts which are moderately to strongly glomeroporphyritic, and tiny euhedral groundmass granules or prisms. Individual phenocrysts are generally about 0.5 to 1.5 mm long. They are pale brown, greenish brown, brownish green, pinkish brown (rarely) or yellowish green (very rarely), and some show slight to moderate oscillatory zoning. Many contain small irregular to rounded inclusions of plagioclase, magnetite, and commonly olivine; a few are packed with small fine-grained dark groundmass inclusions. Clumps of augite phenocrysts commonly contain olivine phenocrysts which are in many examples completely mantled by augite or plagioclase phenocrysts, or both.

Olivine (4 to 20%) occurs as generally small (0.2 to 1 mm) subhedral to euhedral phenocrysts, and smaller euhedral crystals in the groundmass. Some phenocrysts are clumped with augite; others are composite and aggregates reach 3 to 5 mm across. Single phenocrysts are up to more than 3 mm long. The olivine has narrow pyroxene or magnetite rims in a few rocks; in a few others it is slightly embayed. Rare large phenocrysts show well developed deformation lamellae. Partial to complete alteration to iddingsite, or bowlingite, or combinations of chlorite, opaque minerals, talc, biotite(?), and calcite is very common. Optic axial angles are generally 87 to 90°, indicating compositions close to Fo_{80}.

Magnetite (3 to 10%; generally 5 to 7%) occurs as subhedral to irregular microphenocrysts, commonly aggregated with pyroxene and olivine, and small (up to 0.05 mm) euhedral crystals in the groundmass. It is titaniferous, but rarely contains ilmenite lamellae.

Potash feldspar (1 to 4, generally 2-3%) occurs as narrow but prominent to very narrow rims on plagioclase phenocrysts and smaller crystals, and as an evenly distributed interstitial phase in the groundmass. In a few rocks, coarse-grained sanidine has crystallized in and around large clumps of phenocrysts. The remainder of the potash feldspar is presumably also sanidine.

Hornblende (trace to 1%) is present in a few of the more silica-rich rocks as small relict phenocrysts partly to wholly replaced by initially rim-forming fine-grained pyroxene and magnetite. It is yellow-brown or green brown; in one rock the pleochroism scheme is:
α = pale yellow-brown, β = yellow-brown to greenish yellow-brown,
γ = brownish green to green.

Biotite (trace to 1%) occurs in some of the most basic, mafic-rich shoshonites, where it occurs as small flakes in the groundmass, in rims around olivine, or in hornblende pseudomorphs. It is bright golden or yellow-brown, pale yellow-brown to golden brown, or very pale straw to deep red-brown. In the rock in which it occurs around olivine, it is very pale brown or pinkish brown to golden or orange-brown, and yellow-green of yellowish green in some orientations. In this rock the biotite occurs as ragged crystals generally surrounded by sericite, then commonly by a zone of plagioclase around a central olivine phenocryst.

Apatite occurs in trace amounts as tiny clear euhedral prisms, commonly included in magnetite, or ferromagnesian silicate phenocrysts.

Hornblende-2-pyroxene andesites

The andesites consist of plagioclase, augite, hypersthene, hornblende, and small magnetite phenocrysts in a fine to very fine-grained groundmass of plagioclase, augite, hypersthene, magnetite, small amounts of hornblende and potash feldspar, and accessory apatite. Olivine is present in many of the andesites, and traces of biotite are present in a few; there is no tridymite, even in the least mafic types. The most prominent feature of these rocks is the large hornblende phenocrysts, which are up to 6 mm or more long. The plagioclase phenocrysts are more abundant (7 to 30%) but slightly smaller (0.1 to 3.8 mm, generally about 0.5 to 1.5 mm) and less prominent.

One rock from the crater area is leucocratic hornblende-pyroxene microdiorite made up of 1-2 mm plagioclase crystals (80%), yellow-brown hornblende prisms 0.2 to 5 mm long (10%), small augite prisms (5%), magnetite (3%), small amounts of hypersthene, biotite, apatite, and olivine, and a trace of potash feldspar. The apatite is unusually abundant, or perhaps simply unusually coarse-grained, and has a red-brown colour probably due to included hematite. It is probably a high level intrusive rock, either from a plug or a large dyke.

Plagioclase (62 to 80%, generally about 70%) is similar to that in the shoshonites except that it is less commonly clumped, tends to have more inclusions, and is more sodic. Some phenocrysts have highly spongy, or corroded, inclusion-filled cores, or calcic cores cut by irregular fractures filled with very pale pink-brown isotropic glass(?).

Augite (3 to 25%, commonly about 15%) occurs as phenocrysts or microphenocrysts, or both 0.1 to 3 mm long, and commonly 0.3 to 0.5 mm or 0.7 to 1.2 mm long, and much smaller euhedral groundmass prisms. The phenocrysts are commonly clumped together, or with various combinations of hornblende, hypersthene, plagioclase, magnetite, and olivine phenocrysts or microphenocrysts; a few have cores of hypersthene. Colour ranges from very pale brown, through brown-green and green-brown, to faint green. Under crossed polarizers, there is some dispersion and anomalous blue, and rare hourglass structure. It is probably a slightly aluminous calcic augite.

Hypersthene (1 to 10 or 12%) occurs as small euhedral prisms, generally elongated, but not commonly of phenocryst size; the largest crystals are 0.6 to 1.4 mm long. It is commonly rimmed by augite or surrounded by small augite phenocrysts; less commonly it forms cores in augite, or complex intergrowths with augite and magnetite, possibly after olivine or hornblende. It also occurs in reaction rims on olivine.

Hornblende (trace to 12%) forms small to large commonly zoned phenocrysts and uncommon groundmass crystals in all except one of the andesite varieties. As in all other Highlands volcanic rocks, it is rimmed or variably replaced by fine-grained pyroxene and magnetite. In rocks where the hornblende is most abundant and green, it is least affected, and rims may be absent on some crystals; these rocks are generally the most acid andesites. In the more basic rocks, it is browner and has broad rims or is completely replaced; the smallest crystals are the first to be totally replaced, or oxidized. Pleochroism schemes vary as follows:

α = pale to very pale yellow-brown

β = shades of greenish yellow-brown, yellow-brown, or brownish green

γ = shades of greenish brown, brownish green, amber brown or zoned from yellowish brown or brownish green (core) to green (rim)

Zoning is most prominent in the greenest, least oxidized hornblende, which also tends to have greater absorption in the than in the direction.

Magnetite (3 to 7%) is similar to that in the shoshonites, except that microphenocrysts are more common, it occurs in rims, etc. on or after hornblende and olivine, and it contains more ilmenite. Some magnetite in the more weathered or altered rocks has been partly to wholly oxidized to hematite.

Potash feldspar (trace to 2%) occurs as extremely narrow rims on plagioclase crystals, and interstitially in the groundmass. It is probably sanidine.

Altered rocks

Some of the specimens, including one from outcrop, collected in Bosavi crater are of altered or metamorphosed rocks, and one is a calcareous (calcitized) volcanolithic grit. One altered basalt consists of plagioclase phenocrysts extensively fractured and altered (to sericite and calcite), relict augite phenocrysts largely replaced by various combinations of magnetite, chlorite, actinolite, calcite, and epidote, olivine phenocrysts altered to chlorite and magnetite, and some primary magnetite in a recrystallized groundmass. The groundmass is made up of plagioclase (probably albite), sericite, patches of calcite, chlorite, actinolite, magnetite, and some leucoxene. Relict augite phenocrysts are commonly mantled by calcite, then an outer zone of actinolite and magnetite with patches of chlorite and scattered epidote cyrstals. Groundmass augite prisms are replaced by green pelochroic actinolite, and magnetite. Another type has a relict porphyritic texture, with 'ghost' phenocrysts containing some relict plagioclase and augite in a recrystallized matrix of albite, tremolite-actinolite, epidote, chlorite, leucoxene, and magnetite. Plagioclase has altered to albite and calcite, with or without some epidote, augite has altered to tremolite-actinolite and opaque mineral(s) with or without calcite, or epidote, or both, and olivine is replaced by chlorite, **tremolite-actinolite, and opaque oxides.**

DISCUSSION

The lavas of Mount Bosavi are more basic, or more predominantly basaltic (shoshonitic) and appear to be higher in potassium than any of the lavas from the other volcanoes described in this report. However, systematic sampling from outcrop, particularly in the crater walls, would be needed to verify the volume and time relationships between the shoshonites and the andesites. The apparent absence of intermediate olivine-2-pyroxene and 2-pyroxene basalts may also be a sampling effect.

If the specimens are representative, then there is a distinct bimodality in the composition of the lavas. The presence of metamorphosed olivine basalts and an intrusive andesitic rock in the crater suggests that the andesites may be significantly younger than the shoshonites (or olivine basalts) and their intrusion into the volcanic pile accompanying their eruption metamorphosed the basalts. The andesites could be the products of prolonged differentiation in a magma chamber beneath Mount Bosavi.

MOUNT MURRAY

GEOGRAPHY

Mount Murray is on the southern boundary of the Southern Highlands District, in the low foothills of the central ranges. It is about 100 km south-southwest of Mount Hagen, about 50 km south of Ialibu, and about 80 km from both Mendi and Kikori. Erave patrol post, which has a C-category airstrip, is about 15 km northwest of the mountain, near the Erave River. Erave is served by regular and chartered light aircraft flights from Mount Hagen. Tsamberigi mission, which has a small D-class airstrip, is on the lower northwest slopes of Mount Murray (Fig. 20). It is linked by walking tracks to the villages of Sau, to the southeast, Ianguri, Oiagi, and Hogulegi on the northern slopes of the mountain, and Yaka and Maseu in the eroded crater. Apart from small areas in and around these villages, Mount Murray is entirely forested. These areas, and rare places in rivers, afford the only helicopter landing sites on and around the mountain. There are numerous tracks over most of western and northern slopes, several within the crater area, and a few on the southwestern and southeastern slopes. Few if any tracks extend far south of Maseu village. Streams are generally open, boulder-strewn, and easily walked along, except after heavy rain. Progress is halted high in the headwaters by dense tangled undergrowth, or by high waterfalls.

MORPHOLOGY (Fig. 21)

Mount Murray is a deeply eroded simple central-type stratovolcano which straddles a series of alternating west-northwesterly limestone ridges and valleys underlain by shale. The summit ridge is a roughly horseshoe-shaped range of flat-topped hills separated by deep V-shaped notches (Fig. 22). The highest point is 2254 m above sea level, about 1300 m above the average height of the surrounding country. Enclosed by the summit ridge on three sides is the deeply eroded crater area which is now a composite of numerous amphitheatre-headed valleys up to 1000 m deep (Figs. 21, 23). The valleys are separated by steep-sided almost knife-edged ridges which slope steeply at their outer ends to the almost flat alluvium-covered floor of the crater area. Between Anisu and Kiskai creeks is an area of low hills, some of which are limestone strike ridges. The southern and southeastern parts of the volcano have been almost completely eroded away, leaving a few flat-topped remnants on moderately to highly dissected or karst limestone.

The other slopes of the volcano are relatively well preserved, particularly on the northwest side. They are cut by V-shaped valleys which are up to 200 m deep at their upper ends, but only 5 to 20 m deep farther downstream. The drainage is nearly perfectly radial close to the summit ridge, but swings to follow the regional strike farther down the slopes. Volcanic rocks have filled the valleys between the limestone ridges on the eastern and western flanks (Figs. 20, 21), extending up to about 25 km from the centre of the volcano. Steep-sided gullies up to 50 m deep have been cut into some parts of these outer-most slopes, especially on the southwest side.

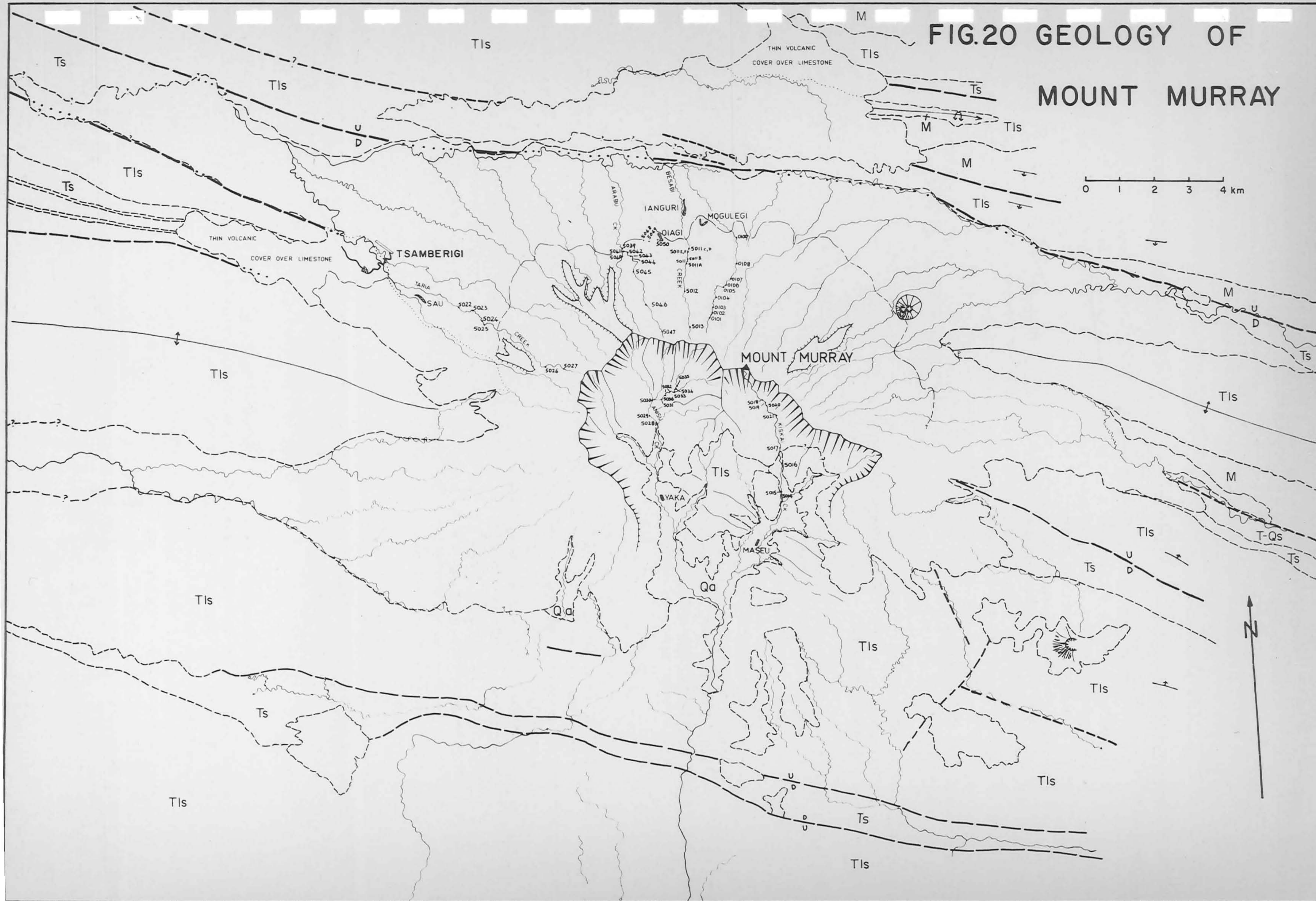
The northernmost part of the volcanic apron, which blankets a series of limestone fold ridges, has been up-faulted about 250 m, isolating it from the remainder of the volcano. About 20 km south of the crater area is a large triangular outlier of volcanic (mainly pyroclastic and lahar) deposits and volcanic-derived sedimentary rocks (Fig. 21). This outlier is separated from the main volcano by an uplifted, deeply dissected limestone block which is cut by a narrow, rift-like valley formed in soft shale and marl. It is also cut by the gorge of the upper Kikori River, and by several actively headward-eroding winding gorges on its southern and eastern sides. On the western side, there is a gradation into very subdued topography developed on soft late Tertiary clastic sediments.

A small satellite cone with a shallow summit crater is situated on the northeastern flank, and a similar but larger cone is isolated on karst limestone to the southeast of the crater area (Figs. 20, 21).

GEOLOGY

Mount Murray is made up of weakly porphyritic olivine basalt and minor hornblende andesite lava, pyroclastic and lahar deposits, agglomerates, and lower on the flanks, volcanic-derived sediments. The slopes and crater walls are almost entirely basaltic, the andesites being restricted largely to dykes and small plugs exposed in the crater area. Rocks in the crater area are commonly altered, and some are mineralized, generally with pyrite.

FIG.20 GEOLOGY OF MOUNT MURRAY



To accompany Record 1973/89

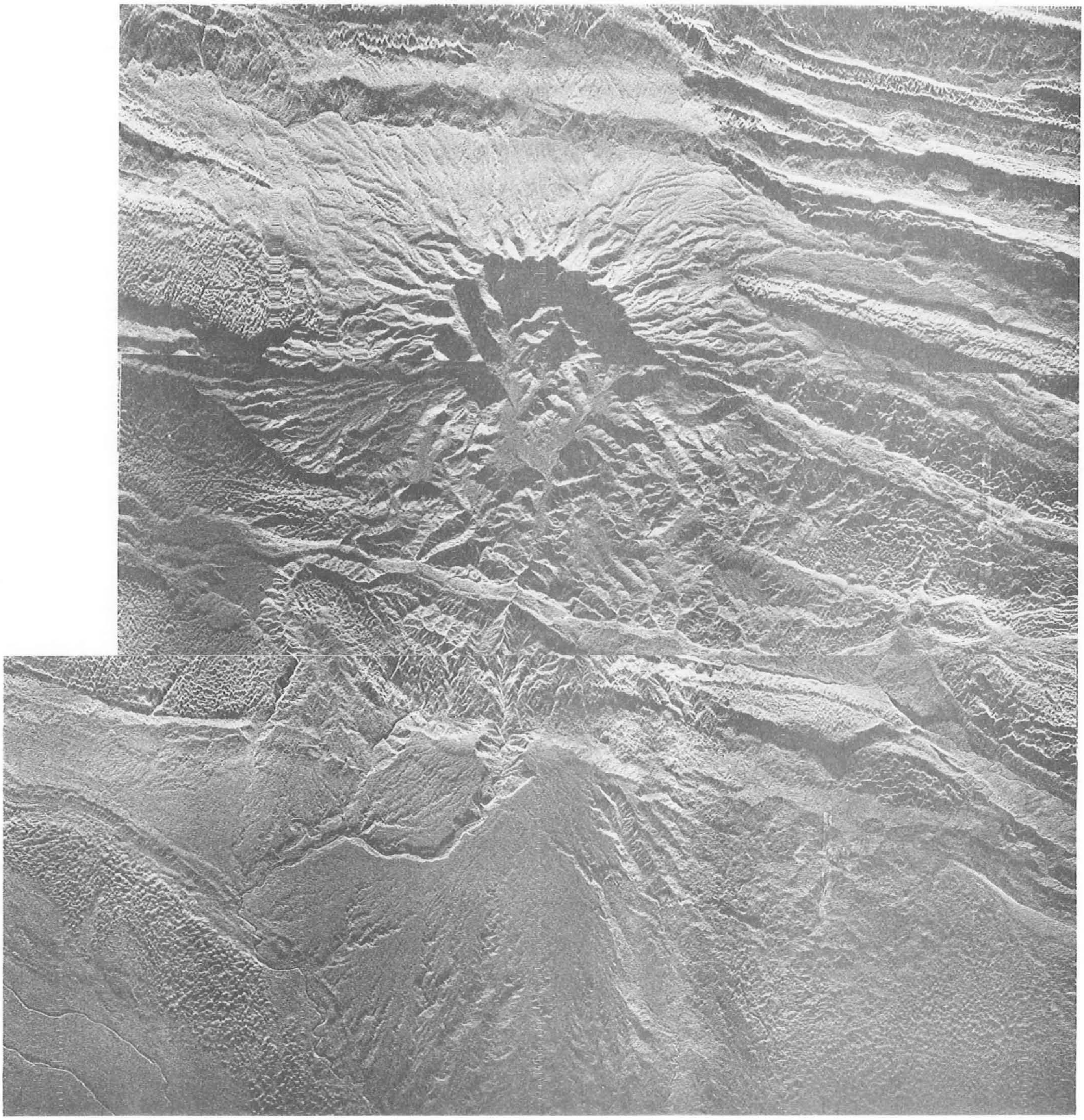


Figure 21. Radar imagery of Mount Murray, at approximately 1:250,000 scale, showing isolated area of volcanic rocks and outwash to the south, and surrounding limestone ridges and shale valleys partly filled by volcanic rocks. Compare with Figure 20. S L A R imagery by Westinghouse-Raytheon, courtesy of the Department of the Army.

Figure 22. Mount Murray from the northeast, about 10 km distant. Neg. 5451.

Figure 23. Part of the eroded crater wall of Mount Murray, from near Yaka village, looking northwest. The valley of the Anisu River runs diagonally from centre right to lower left. Neg. GA/5410.

Slopes

Outcrop in streams on the western and northern slopes is massive to vesicular lava, agglomerate, volcanic rudite, tuff, and volcanolithic arenite. In the Taria Creek on the western flank, outcrops of weathered or brecciated hornblende-bearing andesite are overlain by vesicular porphyritic olivine basalt. The float includes dark grey olivine basalt and medium grey hypersthen-bearing olivine basalt. In the wara Arabu, on the northwest flank, a massive olivine basalt flow with a vesicular top is overlain by agglomerate or multicoloured volcanic rudite, and in places by bedded tuff and volcanolithic sandstone. The agglomerate, which forms a high waterfall at the head of the stream, consists of mainly dark grey rounded clasts in a reddish sandy matrix. Float includes augite-rich olivine basalt, and olivine basalt with a trace of hornblende. Large boulders in soil west of Oiagi village are very dark grey basic olivine basalt, and lighter grey olivine basalt with abundant small plagioclase phenocrysts. Outcrop in Besabi Creek, east of Oiagi, is scarce, and consists of massive olivine basalt flows with brecciated tops, and volcanolithic conglomerates. The float is dominantly olivine basalt, with less common reddish agglomerate. In the unnamed creek farther east, the only outcrop is light to medium grey olivine basalt and 2-pyroxene basalt, with faint flow-banding in places. Float includes olivine basalt, hornblende-bearing olivine basalt, and purple-red agglomerate.

The olivine basalts are characteristically fine-grained with few mafic phenocrysts (augite is the most prominent), but abundant small plagioclase phenocrysts. In the darker rocks, the plagioclase phenocrysts are difficult to distinguish.

Crater area

Outcrop in the eroded crater, around the central exposures of basement limestone (a white to buff foraminiferal limestone) consists largely of massive agglomerate and altered massive and vesicular lavas cut by numerous dykes of hornblende andesite, and rare dykes of olivine basalt or dolerite. In Kiskai Creek, north of Maseu village, dykes of hornblende andesite occur at localities 5014, 5015, 5019, 5020, and 5021 (Fig. 20). At the last three localities, the dykes intrude massive agglomerate. Other outcrops are: hornblende-bearing olivine basalt dyke in agglomerate at 5018, and lava overlain by flat-lying semiconsolidated laminated mudstone at 5017. Float in the stream includes hornblende andesite, fresh and chloritized olivine basalts, and rare olivine-2-pyroxene basalt.

Rocks in the headwaters of Anisu Creek are generally moderately to highly altered, and some are pyritized. At locality 5028, there are massive gorge-forming outcrops of agglomerate and volcanolithic conglomerate. Massive, altered olivine basalt lava with abundant vesicles partly filled by dark bluish-green zeolite, and green chlorite crops out at locality 5029. At the triple stream junction (5030), a dyke of highly altered pyritic andesite about 5 m wide cuts altered vesicular olivine basalt. Farther upstream, the outcrops are: strongly jointed chloritized olivine basalt (5031), chloritized pyritic andesite (5032), a dyke of partly metamorphosed basalt or dolerite (5035), and altered porphyritic microdiorite or andesite

(5036). Float includes highly porphyritic olivine basalts (one with prominent 5 mm plagioclase phenocrysts, another with 3-5 mm augite and olivine phenocrysts), chloritized olivine basalt, hornblende andesite, and very rare olivine gabbro.

Pre-Murray rocks

The rocks underlying Mount Murray volcano and exposed in the crater area are strongly folded and overthrust (to the south) middle Miocene and rare Eocene limestones, upper Miocene and Pliocene fine-grained clastic sediments, and marl and limestone, and rare Upper Cretaceous shale exposed in the cores of anticlines (Figs. 20 & 21). Small folding and faulting movements in the sedimentary sequence have taken place after the formation of the volcano. These have resulted in the upfaulting of the northernmost part of the slopes by a major west-northwesterly trending thrust fault, and the isolation of the area of volcanic rocks and outwash south of the mountain (Fig. 21). Close examination of the airphotographs shows that the small outliers of volcanics south of the crater have been tilted upwards at their southern ends. The two small outliers in the narrow rift-like valley are about 300 m lower than those to the north. The limestone ridge south of this valley is at a higher level than the top of the northern edge of the volcanic outlier. These observations suggest that the area between the volcano and the southern outlier has been up-arched, perhaps with some faulting, and that a narrow rift valley may have formed along the crest of the arch. Subsequent erosion has removed most of the volcanic rocks from the uplifted area. A strong lineament along the northern edge of the outlier may be the extension of a very strong lineament which extends many kilometres to the southeast, near Mount Duau. This lineament appears to be a fault with a small downthrow to the north. The two faults which disappear beneath the western (near Tsamberigi) and eastern flanks of Mount Murray, are roughly aligned with the northern part of the crater wall. One or both of them may have influenced the formation of that scarp.

Post-Murray rocks

Small areas of recent alluvium, which is largely coarse gravel and sand, cover much of the floor of the crater area, a small area southwest of the crater, and parts of the valley floors east and west of the volcano.

PETROGRAPHY

The lavas of Mount Murray can be divided into three main groups: shoshonites and olivine-2-pyroxene high-K basalts, which make up the bulk of the volcano, hornblende-2-pyroxene andesites, and altered or metamorphosed rocks. The two minority groups are virtually entirely confined to the crater floor area.

Basalts

The shoshonites and high-K basalts are weakly porphyritic light to dark grey rocks which consist of small, abundant plagioclase micro-phenocrysts and phenocrysts, and less abundant small to large (up to 5 mm) augite and olivine phenocrysts in a fine-grained holo-crystalline groundmass. Plagioclase laths, augite, olivine, and magnetite granules, interstitial potash feldspar, and commonly minute hypersthene needles make up the groundmass. The most basic rocks contain up to 30 percent augite (7% phenocrysts) and up to 15 percent olivine (5 to 10% phenocrysts). The amounts of augite and olivine drop steadily, hypersthene becomes more common, and plagioclase even more abundant as silica content increases through to the olivine-2-pyroxene basalts.

Estimated percentages by volume are:

Plagioclase	52 to 80	(0 to 35% phenocrysts, generally 15 to 30%)
Augite	10 to 30	(0 to 8 or 9%, generally 2-5% phenocrysts)
Olivine	4 to 15	generally about 7 (0 to 8%, generally 5% phenocrysts)
Magnetite	3 to 12	generally 5 to 6
Potash feldspar	0 to 3	generally 1 to 2
Hypersthene	0 to 5	

Some rocks contain up to 5 percent interstitial glass; these generally lack modal potash feldspar. Apatite is detectable as an accessory phase in many rocks. Traces of hornblende, largely to entirely converted to fine-grained pyroxene and magnetite, with or without plagioclase are present in a few rocks, generally the most siliceous types. Minute blebs of pyrrhotite with traces of chalcopyrite occur in augite and olivine phenocrysts of some of the most siliceous shoshonites.

One rock from the unnamed stream southeast of Mogulegi is a hybrid type consisting of plagioclase (15%), augite (5%), hypersthene (3%), and magnetite (1-2%) phenocrysts in a groundmass of plagioclase (68-70% total), augite (15-17%), hypersthene (5-7%), magnetite (5%), apatite, and relict olivine (each less than 1%). Potash feldspar (2%) forms rims on plagioclase crystals.

Plagioclase in the basalts forms generally small (0.3 to 2 mm, generally about 1 mm) phenocrysts, and small laths or polygonal crystals in the groundmass. In a few rocks, phenocrysts are up to 5 mm or more long. The phenocrysts are moderately to strongly zoned, generally with weak to moderate oscillatory zoning super-imposed on the normal zoning. Some phenocrysts are almost free of inclusions, others contain narrow to broad zones or cores of fine groundmass inclusions, and others contain scattered large irregular inclusions of fine-grained opaque-rich groundmass. In most rocks the plagioclase has vestigial to prominent (0.02 mm wide) rims of potash(?) feldspar. The cores of phenocrysts in a few rocks are cut by numerous irregular, fracture-like veinlets of pale pink or pinkish brown isotropic material which may be glass, or perhaps an alteration product.

Augite occurs as small to large phenocrysts (0.3 to near 5 mm, but generally less than 2 mm) and equant granules or small prisms in the groundmass. It is generally euhedral, or in the larger phenocrysts, composite and rounded. Some phenocrysts are clumped together, or with olivine, or plagioclase, or both. A few have small cores of olivine. In some rocks, the augite phenocrysts have a sponge-like appearance and are packed with irregular groundmass inclusions. The augite is pale brown, green-brown, or green, slightly zoned, and shows slight to moderate dispersion with some anomalous blues at extinction under crossed polarizers. It is probably a slightly to moderately aluminous calcic or diopsidic augite.

Olivine occurs as phenocrysts similar to but generally a little smaller than the augite phenocrysts, and in small quantities in the groundmass. It commonly forms clumps of crystals, with or without augite or plagioclase or both. Rims of orthopyroxene are very rare, even in the hypersthene-bearing rocks; magnetite rims are even less common. Partial to complete alteration to iddingsite, chlorite, opaque iron oxides, talc(?), and serpentine, or various combinations of these is very common, particularly in rocks from the crater area. The optic axial angle (2V) is about 90°, indicating a composition close to Fo_{80}.

Hypersthene occurs as minute needles, or small prisms, or both in some of the basalts. It is most abundant in those with the smallest amounts of augite and olivine. In a few rocks it also occurs as small phenocrysts, generally with augite rims, and as narrow rims on olivine grains.

Magnetite occurs rarely as small microphenocrysts, which are commonly clumped together, and is largely confined to the groundmass where it forms abundant tiny euhedral crystals.

Potash feldspar forms narrow rims on plagioclase crystals and also occurs interstitially in the groundmass of most of the basalts. It is probably sanidine.

Andesites

The 2-pyroxene-hornblende andesites consist of moderately to very abundant plagioclase phenocrysts up to 3 mm long, hornblende phenocrysts, and generally a few augite and hypersthene phenocrysts in a fine to very fine-grained groundmass of plagioclase, augite, hypersthene, hornblende, magnetite, and accessory apatite. Most rocks contain a small amount (trace to 3%) of potash feldspar interstitially in the groundmass and as rare rims on plagioclase, and 3 to 7 percent tridymite as relatively coarsely crystalline patches in the groundmass. One rock from Kiskai Creek (5021) contains 7-8 percent chlorite in patches in the groundmass, in vesicle linings, and replacing groundmass pyroxene. Another (5021) contains a trace of biotite as small phenocrysts. Minute blebs of pyrrhotite partly fringed by chalcopyrite occur in the hornblende, augite, and magnetite phenocrysts of some rocks.

Plagioclase (65 to 80%, 8 to 30% phenocrysts) occurs as strongly oscillatory-zoned phenocrysts and microphenocrysts 0.1 to 1.5, 2, or 3 mm long, and as laths about 0.02-0.04 mm long in the groundmass. The phenocrysts contain scattered or zoned groundmass inclusions, and are commonly clumped together or composite.

Hornblende (trace to 10%) occurs as euhedral, commonly zoned phenocrysts up to 2, 3, or even 5 mm long, and small groundmass prisms. It has narrow rims of fine-grained pyroxene and magnetite, and in one rock is marginally corroded. Pleochroism schemes are:

α	β	γ
faint yellow-brown	greenish yellow-brown	slightly brownish green
pale yellow-brown	dark greenish-brown	brownish-green
pale yellow-brown	deep yellowish-brown	brownish-green
pale yellowish-brown	dark brown to greenish-brown	brownish-green, zoned greenish-brown to green, or with green core

Augite (2 to 8%) occurs as uncommon phenocrysts, generally about 0.5 mm or less, rarely up to 2.5 mm long, in most rocks, and smaller prisms and needles in the groundmass. It is colourless to pale brownish-green or green. Some phenocrysts are composite, or clumped together or with hypersthene.

Hypersthene (2 to 7%) occurs as small prisms and needles in the groundmass, and in one rock (5021) as 0.2 to 1 mm long phenocrysts which commonly have rounded ends.

Magnetite (3 to 5%) occurs as microphenocrysts (0.05 to 0.4 mm) which are commonly clumped together and close to or included in pyroxene and hornblende. It also forms small (0.01 mm) euhedral crystals in the groundmass.

Apatite (trace to over 1%) occurs as euhedral prisms up to 0.5 mm long, commonly closely associated with magnetite or hornblende.

Altered or metamorphosed rocks

Several outcrops in the crater area are of highly altered olivine basalt. These rocks are generally extensively chloritized, and some also contain secondary talc(?), serpentine and opaque oxides (after olivine), and calcite (filling vesicles and after olivine). One rock contains abundant vesicle-filling sheaf-like aggregates of a zeolite with a negative 2V of about 50° and straight extinction: it may be laumontite. The centres of some of the vesicles are occupied by spiky aggregates of pale green chlorite flakes.

The altered pyritic andesite from the dyke at locality 5030 consists of relict and partly kaolinized plagioclase, some of which may be albitized, patches of crystalline quartz and calcite, abundant pyrite euhedra, and clusters of minute leucoxene (**anatase** or brookite) granules.

The metamorphosed rocks at localities 5035 and 5036 in the headwaters of Anisu Creek consist of relict plagioclase and augite phenocrysts in a matrix of actinolite, chlorite, magnetite, and apatite. One (5035) contains small amounts of muscovite or talc, and honey-brown biotite. The other contains 1-2 percent relict hypersthene surrounded by actinolite and chlorite.

Olivine gabbro

The gabbro from float in the headwaters of the Anisu River, in the crater area, consists of plagioclase (65%), augite (15-17%), olivine (10%), potash feldspar (5%), magnetite (2.5-3%), apatite (1.5%), hypersthene (1%), and small amounts of secondary talc(?), chlorite, prehnite, and illite (muscovite). It is the plutonic equivalent of a shoshonite, and could be called a monzonitic (high-K) olivine gabbro. The plagioclase forms interlocking elongate subhedral prisms averaging 0.8 to 0.9 mm long. It shows moderate normal zoning, and some is slightly altered to sericite and prehnite. Augite forms equant crystals 0.2 to 3 mm across and composite grains up to 6 mm across. It has a semi-poikilitic habit, enclosing small grains of plagioclase and magnetite, and larger grains of olivine. The optic axial angle is about 45°. Olivine forms small subhedral to anhedral rounded crystals commonly in aggregates with or without augite, or enclosed in augite. It is partly altered to talc(?), chlorite, and opaque oxides. Potash feldspar occurs in interstitial patches which tend to be equant in shape; it has a very low negative 2V indicating sanidine structure. Magnetite and apatite are both closely associated spatially with augite and olivine. Magnetite forms subhedral to ragged grains, tending poikilitic, up to 0.8 mm across. Apatite forms elongate euhedral prisms up to 1 mm long.

DISCUSSION

When compared with those of the Hagen volcanic complex, the Mount Murray basalts are markedly poorer in augite and olivine phenocrysts, and are more uniform in composition. The rarity of andesites and the compositional gap between them and the basalts suggest only a small amount of crystal fractionation, if that is the mode of origin of the andesites. This would have taken place at a late stage in the evolution of the volcano, and resulted in the emplacement of dykes of andesite in the core of the volcano, and the eruption of rare andesitic lava and possibly pyroclastic debris. Alternatively, the basaltic and andesitic rocks could represent different batches of magma from the source area which was probably in the mantle.

Sulphide mineralization, alteration, and metamorphism in the eroded crater area are associated with the late-stage andesitic activity.

The type of alteration in and associated with the late-stage andesite dykes is similar to that found in the outer, or pyritic zones of some porphyry-type copper deposits such as Panguna, on Bougainville (McNamara, 1968). Further alteration and mineralization, possibly involving base metals, particularly copper, may have occurred farther below the volcano. Detailed petrological and geochemical studies are in progress, and should establish the economic potential, or lack of it, of Mount Murray. General aspects of petrogenesis and economic potential are discussed in a later section.

MOUNTS DUAU AND FAVENC

GEOGRAPHY

Mounts Duau and Favenc are the most isolated of the Highlands volcanoes: they lie near the Purari River, 60 km northeast of Kikori, 85 km southeast of Erave, and 60 km south of Karimui patrol post (Fig. 1). The area is almost entirely covered by dense rainforest and is virtually uninhabited. There is a small village near the Sireru River, northwest of Mt Duau, and a hamlet perched high above the Kuru River about 16 km south-southeast of Mt Duau (just outside the area of Fig. 24). Walking tracks are scarce and difficult to find. Access to the mountains is by boat along the Purari, or, more effectively, by helicopter. Places suitable for landing a helicopter are restricted to the larger streams around the lower flanks of the volcanoes. Some impression of their distribution and location may be obtained from the specimen locality points on Fig. 24, as each of these was visited by helicopter.

MORPHOLOGY

Mount Duau (ca 1850 m) is dominated by a scalloped arcuate scarp open to the southwest and surrounded by slightly to moderately dissected volcanic constructional slopes (Fig. 25). This scarp is 1000 m high and represents an old crater or caldera greatly enlarged by erosion. It is generally smooth or cut by small gullies, but near the summit is deeply embayed by an ampitheatre-headed valley. The upper parts of the slopes of the old volcanic centre (west, north, and east of the summit) are cut by closely-spaced deep V-shaped gorges. Lower down, these gorges become steeper-sided and farther apart so that the lower slopes are better preserved. In most places the slopes are terminated abruptly by cliffs up to 150 m high where the volcanic rocks overlie soft sediments (Fig. 25). On the western side, the slopes of Mount Duau merge with those of Mount Favenc, except where they are separated by narrow tongues and inliers of Pliocene sediments along the Wai-i River and Koro Creek. Other such inliers, surrounded by high cliffs, occur farther to the south and southwest, some beyond the boundaries of Fig. 24.

Enclosed by and filling the old crater or caldera is a younger, smaller volcanic cone with an almost concentric summit crater (Figs. 24, 25). This cone and its apron, which extends many kilometres to the south and southwest, are slightly more dissected than the older centre, presumably because of a higher proportion of clastic deposits. The crater has been enlarged by erosion and breached on its southern side by a deep V-shaped gorge, leaving a central hill which strongly resembles a block tilted steeply to the south. The upper flanks of the cone, particularly on the eastern side, are deeply gorged.

Parts of the southern and southwestern extremities of the older and younger aprons have a hummocky or irregular hilly texture on the airphotographs. This may be due to the presence of lahar deposits.

Mount Favenc is similar to Mount Duau, except that its crater remnants are less well preserved and not easily recognizable. The high arcuate scarp extending east and south from the summit is probably a retreated crater wall, as is the smaller arcuate scarp on the western side of the Abede River (Fig. 24). The scarp west of the summit may be a remnant of a second crater; that on the western side of the Aiowa River is of unknown origin. A deep gorge has been cut by the Abede River through the southern wall of the main crater, exposing the underlying sedimentary rocks.

Irregularities in the lower slopes of Mount Favenc have been caused by a fault with vertical movement on the northern side (producing a subdued scarp), and a gentle monoclinal flexure on the southern side. Both have disturbed and diverted some of the drainage.

Extensive areas of the southern apron have a hummocky surface which is probably due to lahar deposits.

GEOLOGY

Geologists of the Australasian Petroleum Company (1961) reported 'alternating tuffs and agglomerates, with lavas in subordinate proportions' on the flanks of Mounts Duau and Favenc.

Mount Duau

Because all the specimens were collected from river boulders (no lava outcrops were found near the helicopter landing sites), the details of the geology are not known. At all localities, rock types in the float ranged from olivine basalt (shoshonite) to hornblende andesite. Andesite is more common in the streams draining the younger central cone than in those draining the older centre.

Float in the Sireru River, draining the northwest flank of the older centre, includes

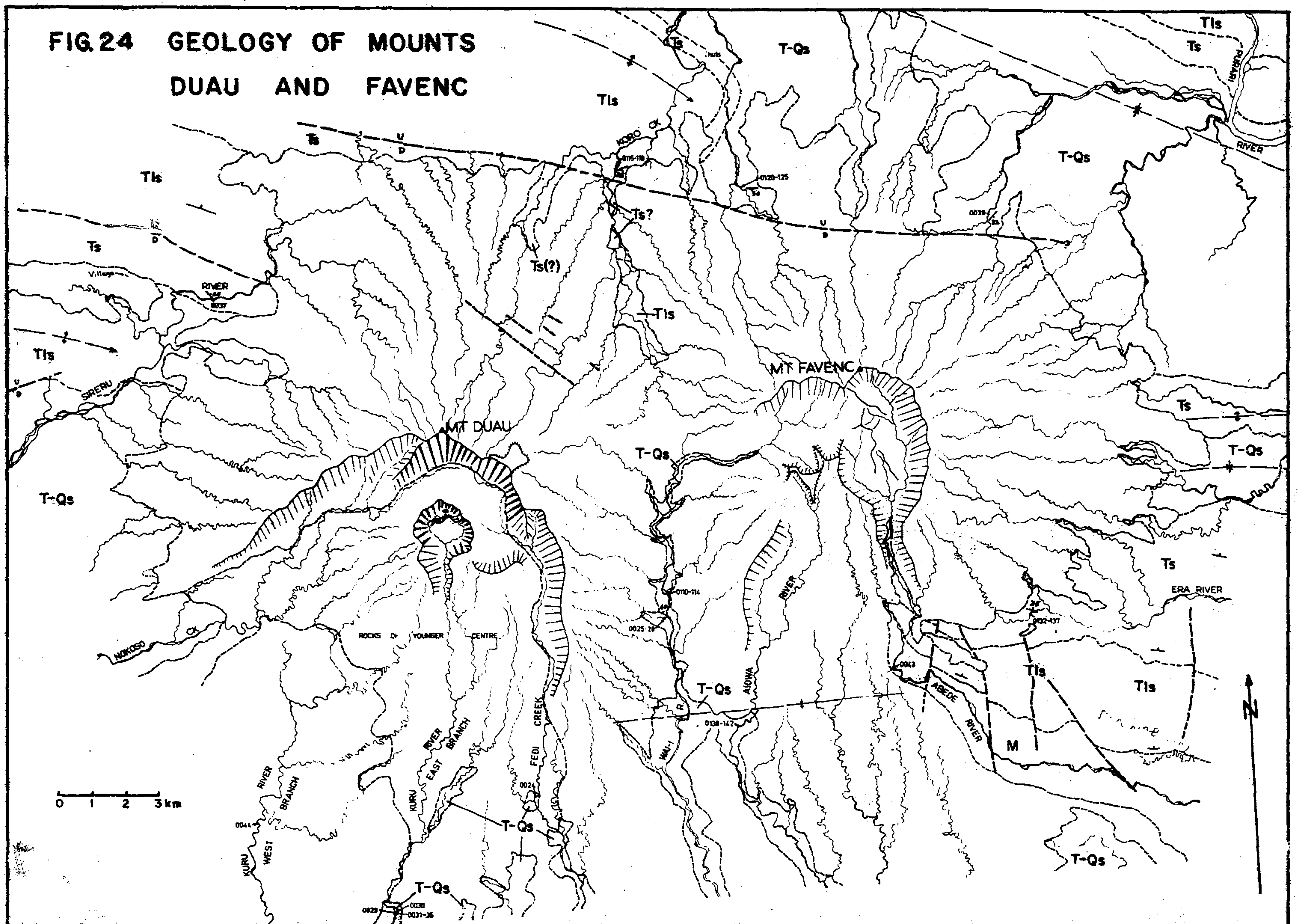
shoshonite (2 specimens)
olivine-2-pyroxene high-K basalt)
olivine-hornblende-2-pyroxene low-silica andesite) 1 specimen of each
hornblende-2-pyroxene andesite)

The outcrop is well-bedded fine sandstone and siltstone which are carbonaceous in part and contain some fossil remains.

The west branch of the Kuru River which drains the western side of the younger cone and part of the older southern apron contains boulders of

Shoshonite)
high-K olivine basalt, or shoshonite) 1 specimen of each
olivine-2-pyroxene high-K basalt, or shoshonite)
hornblende-2-pyroxene andesite)

FIG. 24 GEOLOGY OF MOUNTS DUAU AND FAVENC



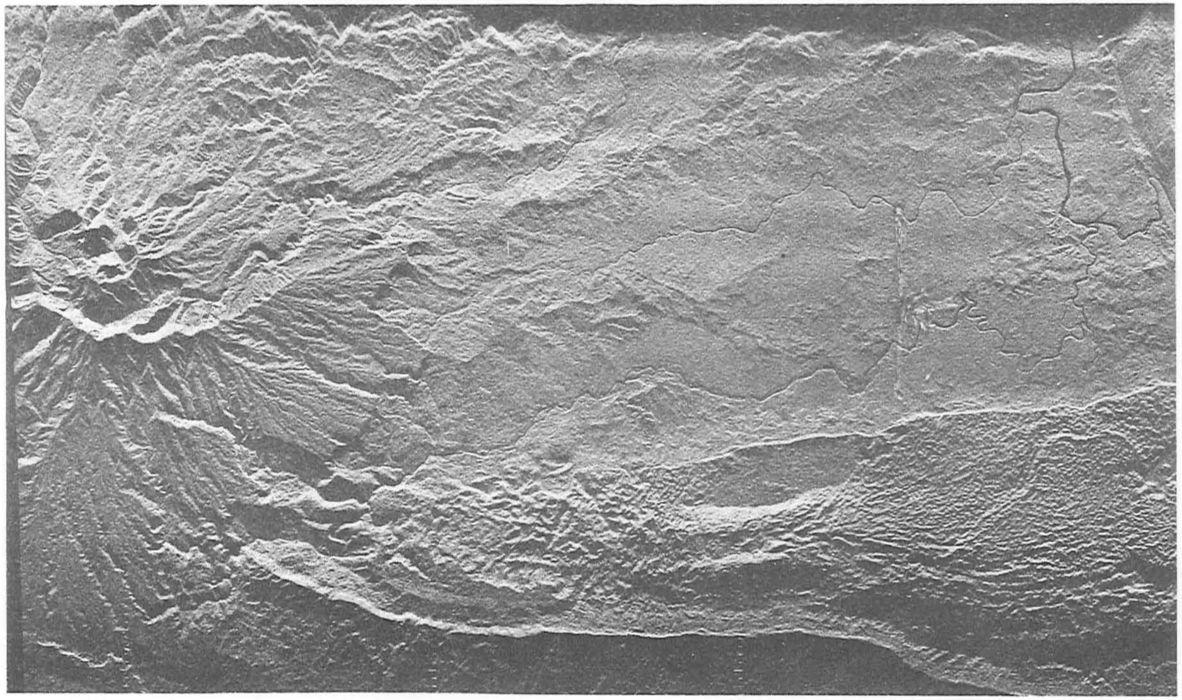


Figure 25. Radar imagery of Mount Duau and the eroded apron to the east. Flat-lying remnants of volcanics occur between Nokoso Creek (lower centre, flowing southwest) and the stream to the north. Upper major stream is the Sireru River; stream at lower left is the Sirebi River. S L A R imagery by Westinghouse-Raytheon, courtesy of the Department of the Army. Scale 1:250,000 approx. Image is reversed to avoid appearance of inverted relief, therefore north is towards bottom of page.

At this locality (0044) there are cliff exposures up to 10 m high of dark semi-consolidated arenites, probably derived from the Duau volcanics.

Float in the east branch of the Kuru River, which drains the crater and the eastern side of the younger volcano, includes

absarokite high-K olivine basalt olivine-2-pyroxene-hornblende hornblende-2-pyroxene andesite hornblende-2-pyroxene high-K andesite/dacite	1 specimen of each

Sandstone with mudstone clasts and some wood fragments, and conglomerate containing some quartzite pebbles crop out at this locality (0029-35).

In Fedi Creek, which flows along the base of the eastern scarp of the older centre and also drains the northeastern flank of the younger cone, the float includes

shoshonite olivine-2-pyroxene high-K basalt (hornblende-)olivine-2-pyroxene high-K basalt (olivine-)hornblende-2-pyroxene andesite	1 specimen of each
hornblende-2-pyroxene andesite	2 specimens

Here, the outcrop is of dark grey-green siltstone and mudstone containing abundant bivalve, gastropod, and plant remains.

The last locality is a small tributary of the Wai-i River, draining part of the eastern flank of the older volcano (0025-28). Here the float includes

shoshonite hornblende-olivine-2-pyroxene basalt hornblende-2-pyroxene andesite	1 specimen of each

The outcrop is siltstone.

Suites of specimens were also collected from float in the Wai-i River (0110-114) and Koro Creek (0115-119), between Mounts Duau and Favenc, but the float could come from either or both of the volcanoes.

Mount Favenc

Float in all streams sampled ranges from olivine basalt (shoshonite) to hornblende andesite, in about equal proportions. There is no noticeable concentration of any rock type in any particular part of the volcano.

At locality 0038, in a tributary of the Purari River draining the northeast flank of the mountain, the float includes

shoshonite	2 specimens

hornblende-olivine-2-pyroxene basalt/low silica andesite	1 specimen of each
olivine-hornblende-2-pyroxene andesite	
hornblende-2-pyroxene andesite	

The outcrop is of well bedded carbonaceous siltstone and fine to medium-grained sandstone.

The stream east of Koro Creek (0120-125) on the north-northeast flank contains boulders of

shoshonite	3 specimens
hornblende-2-pyroxene andesite	2 specimens
(hornblende-)2-pyroxene andesite	1 specimen

Dark grey and black laminated silty mudstone with flaggy to blocky jointing crops out in the area.

Specimens collected from float in the Aiowa River, on the south-southeast flank are:

shoshonite	3 specimens
hornblende-2-pyroxene andesite	1 specimen of each
hornblende-(2)-pyroxene andesite/dacite	

Almost flat-lying mudstone and siltstone crop out at this locality (0138-142).

In the Abede River, which drains the creater area, the float includes

shoshonite	2 specimens
olivine-2-pyroxene high-K basalt	1 specimen
olivine-hornblende-2-pyroxene andesite	3 specimens

The outcrop is massive carbonaceous fine sandstone overlain by at least 40 m of very crudely bedded volcanic arenite.

Float in the Era River, on the southeast flank (0132-137), includes shoshonite and hornblende-2-pyroxene andesite. It was noted that three main rock types were present as float: dark basaltic rocks, light grey rocks rich in plagioclase phenocrysts, and light grey rocks with conspicuous hornblende phenocrysts. Outcrop at this locality is finely laminated mudstone and siltstone.

Pre-Quaternary rocks

Mounts Duau and Favenc are underlain by a folded and partly faulted sequence of middle Miocene limestone, upper Miocene marine siltstone, fine sandstone, and mudstone, and Pliocene sandstone, siltstone, and mudstone. Upper Cretaceous(?) siltstone and mudstone in the core of an anticline crop out along the Abede River, but do not appear elsewhere in the area. The limestone is white to pale buff, foraminiferal, and shows a well developed karst topography. Both the upper Miocene and Pliocene sediments are well bedded or laminated, and are similar in lithology. The Pliocene sediments, however, are carbonaceous, highly fossiliferous in places, and are in part terrestrial; fragments of wood and plant remains are present in places (Kuru River east branch, Fedi Creek), and there is some conglomerate (Kuru River). Fossils include bivalves and gastropods.

The extension of sedimentary rock outcrops along streams to within short distances of the volcanic centres (e.g. Wai-i River, Abede River, Koro Creek) suggests that the volcanic piles are quite thin and rest on an up-arched or domed basement. This uplift may have been caused by the emplacement of sub-volcanic intrusions.

PETROGRAPHY

Mount Duau

The lavas of Mount Duau range from olivine-rich absarokite and shoshonite through olivine-bearing intermediate types containing hypersthene with or without hornblende to olivine-bearing and olivine-free hornblende-2-pyroxene andesites. One rock from the younger volcano contains 5 percent tridymite and may be a dacite. There is a steady increase in the amount of hypersthene through the series as olivine decreases in amount and finally disappears, hornblende appears and increases in amount, and finally tridymite appears. Augite is considerably more abundant in the absarokite, shoshonite, and more olivine-rich intermediate types than in the andesitic rocks.

The absarokite and shoshonite consist of large phenocrysts of olivine and augite (gen. 0.3 to 2 mm), smaller plagioclase phenocrysts (0.3 to 1 mm) and rare magnetite microphenocrysts in a groundmass of plagioclase laths, augite, magnetite, some olivine, and interstitial potash feldspar. Brown interstitial glass occurs in some rocks, and some contain up to 2 percent hypersthene, either as minute needles in the groundmass or small phenocrysts. One rock contains a trace of basaltic hornblende. The plagioclase is zoned from bytownite or labradorite to andesine or oligoclase, and makes up about 40 percent of the absarokite and 55 to 70 percent of the shoshonite. Augite ranges from 17 to 25 percent in the shoshonite to 30 percent in the absarokite, and olivine from 3-12 percent to 20 percent. Magnetite makes up 3 to 7 percent of these rocks, and potash feldspar 1 to 5 percent. Apatite occurs in trace quantities.

The (hornblende-)olivine-2-pyroxene basalts are similar to the shoshonite but contain 0 to 5 percent of hypersthene phenocrysts and 2 to 15 percent total hypersthene; augite varies inversely from 20 to 12 percent. Potash feldspar is less common than in the shoshonites, and basaltic hornblende appears sporadically.

One rock from the Sireru River (0037C) is intermediate between the olivine-2-pyroxene basalts and the olivine-bearing andesites, and contains an abnormally large (1.5 cm) basaltic hornblende phenocryst with a narrow magnetite-pyroxene rim and wide calcite mantle. It consists of small plagioclase phenocrysts and groundmass laths (55%), augite (20%), hypersthene (7-10%), and olivine (2%) phenocrysts and groundmass granules, some small hornblende phenocrysts (3%), fine-grained magnetite (5%), and interstitial potash feldspar (1%). The olivine, originally 5 percent or more of the rock, has been largely altered to chlorite and calcite.

The andesites contain phenocrysts of plagioclase (0.3 to 2 mm, generally about 0.5 mm) and hornblende (up to 6 mm, average 0.5 to 2 mm long), usually with some small augite phenocrysts and, in some rocks, hypersthene phenocrysts. Relict olivine phenocrysts occur in a few rocks. Magnetite microphenocrysts are ubiquitous but only form up to 2 percent of the rock. The groundmass consists of plagioclase laths or a mosaic, augite and hypersthene prisms, very fine-grained magnetite, usually a little hornblende and interstitial potash feldspar, and accessory apatite; glass is uncommon. Patches of tridymite (up to 7%) occur in some lavas from the younger centre. These rocks are gradational into dacite. Plagioclase content ranges from 60 to 75 percent, hornblende from 2 to 15 percent, hypersthene 6 to 15 percent, augite 3 to 7 percent, magnetite 3 to 4 percent, and potash feldspar from a trace to 2 percent.

Plagioclase in the Duau lavas forms phenocrysts with weak to moderate (rarely strong) oscillatory zoning superimposed on moderate to strong (rarely weak) normal zoning. Inclusion-filled cones or zones are common. Compositions range from bytownite or labradorite in the cores to andesite or oligoclase at the rim. In the more basic rocks, the plagioclase is more calcic than in the andesites, and usually has a narrow mantle of potash feldspar. The inclusions are generally fine-grained opaque-rich groundmass material. Groundmass laths are unzoned or weakly to moderatley normally zoned and are in the andesine compositional range.

Hornblende forms euhedral phenocrysts up to 6 mm or more long, and smaller euhedral groundmass crystals, all usually with rims of fine-grained pyroxene and magnetite with or without plagioclase. The rims range in width from less than 0.01 to 0.1 mm, or completely replace the smaller crystals. Pleochroism is: α = pale yellow-brown, β = medium to dark yellowish or greenish brown, γ = greenish yellow-brown, greenish-brown, brownish-green, or deep yellow-brown. It is a basaltic hornblende with various degrees of oxidation as indicated by the intensity of the brown colour.

Hypersthene forms euhedral prisms of all sizes up to over 1 mm long; many have partial or complete augite rims, while some form cores in augite phenocrysts. Hypersthene is also present in rims or mantles on some olivine crystals. Pleochroism is weak to moderate from faint green to faint or light pink, or pinkish red.

Augite forms large, composite phenocrysts, smaller euhedral phenocrysts, and small groundmass granules in the basaltic rocks, but is rare as phenocrysts in the andesitic rocks. It also forms rims on hypersthene in some specimens, and rims or mantles with hypersthene on olivine in others. It is faint green, green-brown, or brown, and probably calcic or diopsidic augite in composition.

Olivine occurs only in the basaltic rocks (shoshonites, intermediate types) and rarely as relict phenocrysts in the andesites. It forms subhedral to euhedral phenocrysts up to 2 mm long, commonly composite or clumped with augite, and smaller euhedral microphenocrysts and groundmass crystals. In some of the more siliceous (intermediate) rocks and in the andesites it has reaction rims of hypersthene, augite, and magnetite. It is commonly partly to wholly altered to bowlingite, chlorite, and (?)talc or (rarely) iddingsite. In the absarokite, the larger olivine phenocrysts have deformation lamellae, and some are corroded or embayed, or have mantles of augite microphenocrysts; some of this olivine may be from disintegrated inclusions.

Potash feldspar (sanidine where identifiable) forms rims on plagioclase crystals and interstitial patches in the groundmass of the basaltic rocks, particularly in the shoshonites, and occurs interstitially in some of the andesites.

Tridymite forms small (0.5 mm) patches of wedge-shaped or polygonal grains (cross-sections of 'wedges?) in the groundmass, or smaller rounded clusters of radiating crystals on the walls of cavities.

Mount Favenc

The lavas of Mount Favenc, like those of Mount Duau, range from shoshonite or absarokite to hornblende-2-pyroxene andesite or perhaps dacite, but have a more bimodal frequency distribution. The shoshonites as a group are richer in olivine than those from Mount Duau, and there are few representatives of the rock types intermediate between shoshonite and andesite. Phenocrysts are larger on the average in the Favenc lavas than in the Duau lavas.

The shoshonites consist of phenocrysts of plagioclase (generally 0.3 to 1.5 or 2 mm) augite (0.5 to 2 or 3 mm), and olivine (0.3 to 2 mm), and some microphenocrysts of magnetite in a groundmass of plagioclase laths, augite granules, fine-grained magnetite, some olivine, interstitial potash feldspar, and commonly needles of hypersthene. Apatite is commonly detectable as an accessory phase. A trace of hornblende is present in one rock; originally it amounted to about 1% of the rock, but now has been almost entirely converted to fine-grained pyroxene and magnetite with or without plagioclase. The augite is commonly in clumps which are up to 6 mm across; olivine, some of which has deformation lamellae, is less commonly clumped, and some is clumped with or mantled by augite. Generalized mineralogical composition is:

plagioclase	50 to 68 percent
augite	17 to 25 percent
olivine	6 to 15 percent
magnetite	3 to 6 percent
potash feldspar	1 to 4 percent
hypersthene	0 to 3 percent

Intermediate rock types are olivine-2-pyroxene basalts and olivine-hornblende-2-pyroxene andesites. The basalts differ from the shoshonites in having less augite (13 to 17%), olivine (2 to 14%), and potash feldspar (1-2%), and more hypersthene (6 to 12%). One rock contains about 1 percent hornblende now completely replaced by fine-grained pyroxene, magnetite, and plagioclase. The andesites consist of phenocrysts of plagioclase (up to 3 mm), hornblende (0.2 to 3 mm), hypersthene (0.1 to 1 mm), and minor augite (up to 1.3 mm) and relict olivine in a fine-grained groundmass of plagioclase, hypersthene, augite, magnetite, some hypersthene, and accessory apatite. Potash feldspar occurs as narrow rims on plagioclase crystals. Tridymite (1-2%) occurs in one rock, another contains a trace of biotite (pale greenish yellow-brown to very deep reddish brown), and several contain interstitial glass (up to 7 percent). Mineralogical compositions are in the range:

plagioclase	60 to 65 percent
hornblende	2 to 12 percent
hypersthene	10 to 15 percent
augite	6 to 10 percent
magnetite	3 to 5 percent
olivine	trace to 2 percent
potash feldspar	1 to 3 percent

Hornblende-2-pyroxene andesites from Mount Favenc consist of generally small (0.5 to 1 mm) phenocrysts of plagioclase and hypersthene, generally a few small augite and larger (generally 0.5 to 2 or 3 mm, some to 6 mm) hornblende phenocrysts, and a fine-grained groundmass of plagioclase, hypersthene, augite, generally some hornblende, magnetite, a little potash feldspar, and accessory apatite. Trace amounts of biotite are present in a few specimens, and a few others contain a trace of relict olivine. Tridymite (2-3%) is present in only one rock, a hypersthene-rich type. One rock, from the Aiowa River, contains about 10 percent interstitial glass and a very small quantity of ferromagnesian minerals (including a trace of elict olivine); it may be a dacite. Estimated mineral percentages are as follows:

plagioclase	63 to 80 percent
hornblende	trace to 10 percent
hypersthene	5 1o 18 percent
augite	2 to 10 percent
magnetite	3 to 6 percent
potash feldspar	trace to 1 or 2 percent

Augite and magnetite are less abundant in the more siliceous rocks than in the more basic ones.

Properties of the individual minerals are similar to those of the Duau lavas. However, augite and olivine have a greater tendency to clump together, olivine is fresher and in some rocks exhibits deformation features. The hornblende is yellow-brown to brown, rarely greenish-brown or brownish green as in the Duau andesites.

DISCUSSION

Lavas of Mounts Duau and Favenc are similar to those of the Hagen volcanic complex, except that the phenocrysts, especially olivine, are generally smaller, and hypersthene is more abundant, especially in the basaltic rocks. Siliceous andesites and dacites containing 3 percent or more tridymite are much less common in Duau and Favenc than in the central andesitic complex of Hagen.

The field relationships of the basalts and andesites is unknown, except for a suggestion that andesites are more common in the younger central cone of Mount Duau than in its older centre. Therefore conclusions as to their possible petrogenetic relationships are to be made with caution. It appears that the andesites are related to the shoshonites in the same way as they are in the Hagen volcanic complex.

AIRD HILLS

Aird Hills is a group of low rounded hills on a small island in the Kikori River delta, 12 km east-southeast of Kikori, on the Gulf of Papua. The highest hill reaches about 335 m above sea level. From the radar image (Fig. 26), it can be seen that the Hills are made up of four main, dome-like masses arranged in a roughly square configuration. Each hill is irregular in shape and cut by moderately deep short valleys and gullies (Figs. 26, 27). A small village, Ero, is situated on the eastern side of the Hills and affords the only helicopter landing site in the vicinity.

Geologists of the Australasian Petroleum Company (1961) reported mainly 'rubble and fallen blocks' of agglomerate and hornblende andesite, and tuff. Massive and bedded andesitic agglomerate was reported to be predominant, overlying and underlying andesitic lava in places.

Our observations (Johnson & Sweet) were somewhat different to those of the APC geologists. Light grey to white andesitic or dacitic lavas, with a few small black hornblende and large (up to 1 cm or more) pink or white plagioclase phenocrysts are the predominant outcrop in the streams. There is also some lava with smaller plagioclase phenocrysts. Outcrops are generally deeply weathered, and the freshest specimens were collected from float. The form and lithology of the outcrops and the geomorphology of the Hills are strongly suggestive of exogeneous cumulodomes, which may be located on a circular fracture system.

The lavas are all highly plagioclase-rich, leucocratic acid andesites and dacites. They consist of phenocrysts of plagioclase and hornblende in a fine to very fine-grained groundmass of plagioclase, hypersthene, tridymite, magnetite, a little augite and potash feldspar, and accessory apatite. There is a little hornblende present in the groundmass of some rocks, and a trace of biotite in a few. All the rocks are weathered to various degrees, some only very slightly, but others contain up to 5 percent weathering products.

Plagioclase forms phenocrysts of two size groups, 0.1 to 0.5 mm, averaging 0.3 mm, and 1 mm to over 1 cm. The smaller phenocrysts have strong to very strong normal zoning with superimposed weak to moderate oscillatory zoning in the rims or throughout the crystal. The larger phenocrysts have a broad, spongy inclusion-packed calcic core (which gives them their pink or grey colour), and a clear narrow rim which is zoned similarly to the smaller phenocrysts. One large phenocryst has a partly hollow core containing tridymite. The composition of the cores is about An_{80}. Plagioclase also forms small laths or a fine-grained mosaic in the groundmass; it makes up 75 to 88 percent of the rock.

Hornblende occurs as elongated prisms 0.1 to 3 mm, averaging 0.5 mm long, with narrow (about 0.03 mm) rims of fine-grained pyroxene and magnetite. In some rocks, the hornblende is 15 to 100 percent replaced by pyroxene and magnetite. Pleochroism scheme is:

α = pale to faint yellow-brown, or greenish yellow-brown

β = deep yellowish brown, yellow-brown, deep brown to brownish green, or greenish yellow-brown

γ = brownish green, greenish-brown to green, greenish yellow-brown, bright green, deep yellowish to reddish brown, or yellow-brown.

Generally β shows more absorption than γ, and also displays some strong oscillatory zoning. Hornblende content of the rocks ranges from 1 or 2 percent to 7 percent.

Hypersthene forms small (up to 0.3 mm) elongated prisms and fine needles in the groundmass. In a few rocks it contains numerous opaque inclusions, or is partly oxidized to red-brown and opaque minerals. It constitutes 1 to 10 percent of the rock, being highest in the most basic lavas.

Augite (1 to 2%) is a minor, fine-grained component of the groundmass, and in the rims on hornblende.

Tridymite (1 to 10%) occurs as small (0.1 to 0.5 mm) patches of polygonal or wedge-shaped crystals in the groundmass, and in some rocks also interstitially.

Magnetite (2 to 5%) forms small (0.1 to 0.2 or 0.4 mm) microphenocrysts, and 0.01 mm euhedral crystals in the groundmass.

Potash feldspar (trace to 3 percent) occurs as narrow to very narrow (up to 0.01 mm) rims on plagioclase crystals and interstitially in the groundmass. It is probably sanidine.

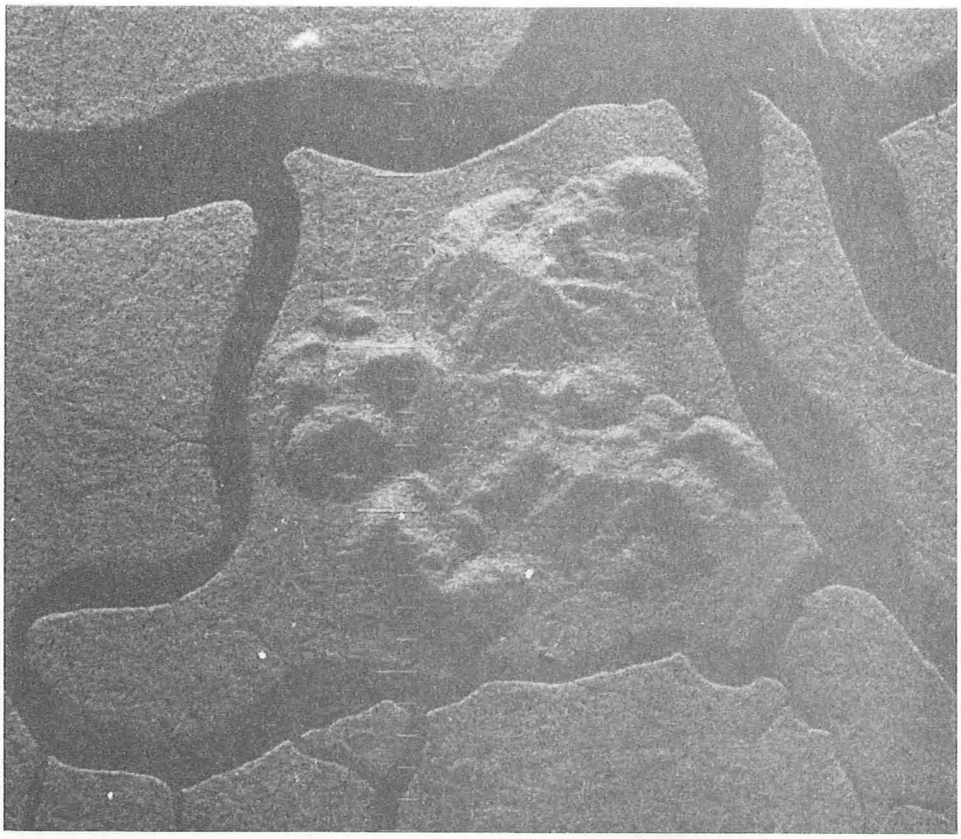


Figure 26. Radar imagery of Aird Hills, at approximately 1:50,000 scale. The hills are on an island in the Kikori River delta. S L A R imagery by Westinghouse-Raytheon, courtesy of the Department of the Army. Image is reversed to avoid apparent inverted relief, thus north is down page.

Figure 27. Aird Hills from the north. Neg. GA/5458.

MOUNT YELIA AND MARBLE PEAK

GEOGRAPHY

Mount Yelia is about 125 km south of Goroka and 130 km west-southwest of Lae in the Eastern Highlands District (Fig. 1). The nearest administrative centre is Marawaka, almost at the foot of the mountain to the northeast (Figs 12, 28), and can be reached only by air from Goroka. The larger centre of Menyamya is about 25 km to the southeast. Apart from Marawaka, population around the mountain is limited to the lower northeast and northwest flanks, and tracks linking these villages to each other and to other areas of population cross and skirt the mountain in several places. Helicopter landing sites are numerous in the summit area and in and around the villages.

MORPHOLOGY

The volcano has a steep-sided conical base and a broad, dome-like summit area, and rises about 1500 m above the surrounding valleys (Fig. 29). The survey point on its summit is 2737 m above sea level. On its northern flank is a group of four domes ranging from low (about 50 m high) and rounded to steep-sided and about 4-500 m high (Figs 29 & 30); another small dome is situated high on the southern flank. To the northwest is the deep broad valley of the Vilolo River, and to the southwest and east those of two of its tributaries. These valleys separate the volcano from the surrounding rugged mountains 2000 to 3000 m high. South of Mount Yelia, and separated from it by a 2700 m saddle, is Marble Peak, or Mount Marble, a long arcuate ridge with a very steep, scarp-like western side (Fig. 29). West of this scarp is a lower horseshoe-shaped ridge with a steep inner side; on the oblique airphotographs (Fig. 29) this ridge resembles the rim of a horseshoe caldera. Marble Peak is a considerably older volcanic centre than Mount Yelia.

Lava flows from Mount Yelia have blocked the Vilolo River and the stream east of the mountain, and have produced flat sediment-filled valleys, including that on which Marawaka is built. Plant and small animal remains, now calcitized, occur in lacustrine sediments near the Marawaka airstrip.

The summit area consists of a southern remanent crater wall (Figs 28, 29, 31) which has been partly obliterated by the large central dome and crater complex and a rounded, slump-like coulée. The coulée is flat-topped, and has steep, rounded sides; it appears to have originated from a small crater on the side of the central dome (0015). The structure of the central dome is complex, with at least eleven craters and pit craters up to 200 m in diameter scattered over its upper surface. An arcuate scarp about 50-60 m high and 750 m long on the eastern side of the dome may be a remanent crater wall, or a collapse fault scarp. A strong lineament, which may be a fault trace, cuts the northern end of this scarp, and appears to coincide with the northern wall of one of the small breached craters on the eastern side of the dome. Immediately east of the survey point on the summit is a very deep, almost sheer-sided and amphitheatre-headed valley which may have been an avalanche valley. Another deep gorge extends from the eastern end of the southern crater wall, but this is probably purely erosional. The cumulodome between the central dome and southern crater wall is about 400 m high, very steep-sided, and has a small shallow depression about 80-100 m in the centre of its almost flat summit area. There is a small shaft-like pit crater on the southwestern edge of this summit area.

The northern domes fall into two groups, the two larger eastern ones, with summit craters, and the two smaller rounded western ones. Both the eastern domes are steep-sided, almost flat-topped, and markedly asymmetric. The more northerly one drops steeply away to the Vilolo River on its northern side, and has a low, rounded southern side. The largest of the domes is elliptical in plan and has moderately gullied 40° slopes, a rounded top, and a shallow, steep-walled horseshoe-shaped crater in the southwestern corner of the summit area.

ACTIVITY

Current activity on Mount Yelia is restricted to a few sulphurous fumaroles along the base of the southern crater wall and at the foot of the cumulodome in the southern part of the main summit area. These fumaroles are cool to cold, and have deposited sulphur and a little pyrite on the surrounding rocks (Branch, 1967).

GEOLOGY

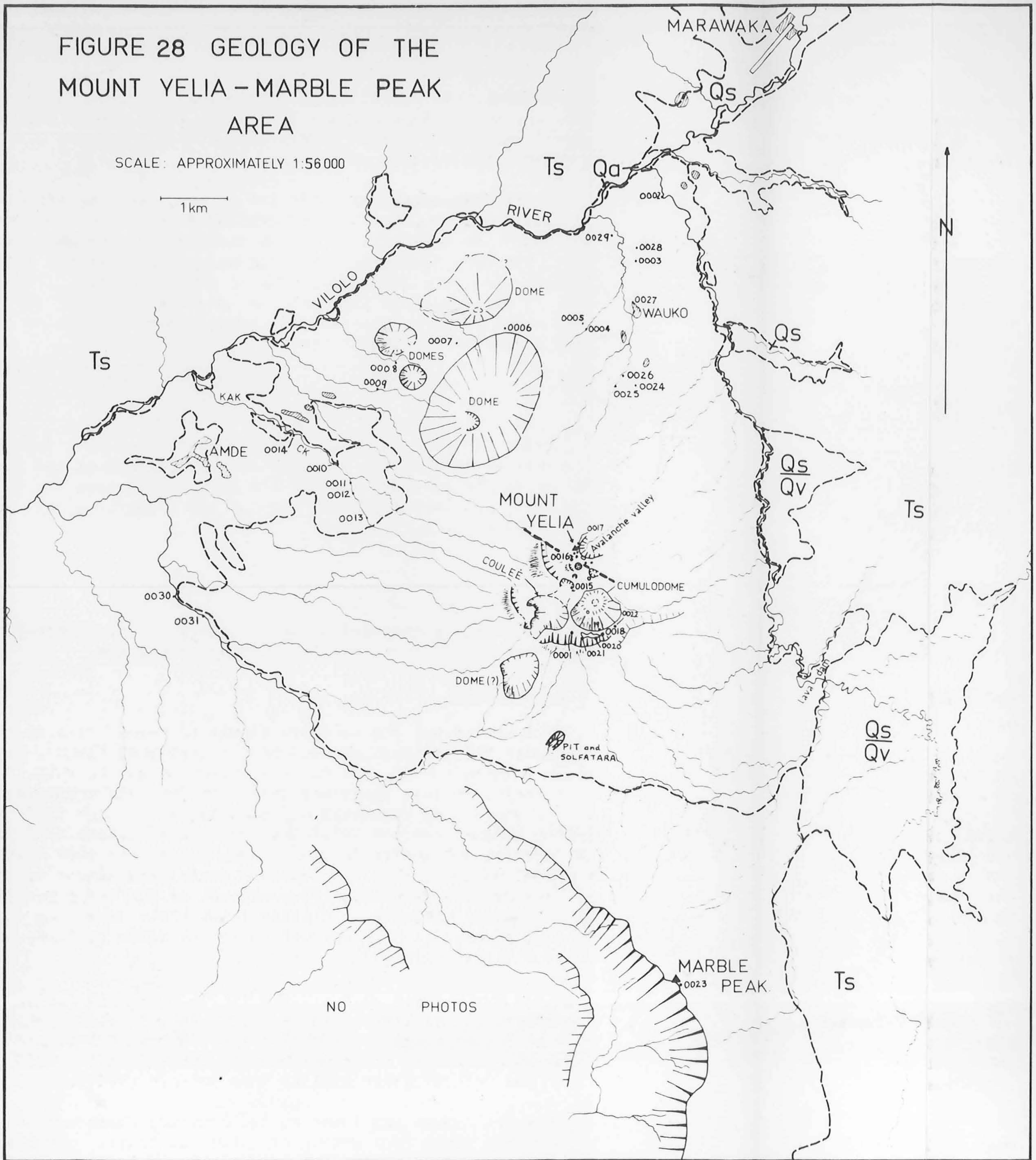
Mount Yelia is composed almost entirely of hornblende-pyroxene andesite and rare dacite lava, ash, and derived sediments.

Lower slopes and domes

Exposures around the northern flanks of Mount Yelia are of massive, unsorted volcanic rudite (such as 0002 on the northeast flank), lava flows up to over 30 m thick (0003), and minor agglomerate and breccia. The ratio of clastic material to lava increases away from the main eruptive centre. At point 0002, about 3 km southwest of Marawaka, 100 m high cliff exposures reveal crudely bedded unsorted indurated rudite with blocks of 2-pyroxene-hornblende andesite and dacite to 1 m across. A nearby road cutting exposes deeply weathered volcanolithic conglomerate containing clasts up to 1.5 m in diameter. The massive 30 m thick flow exposed at 0003 is porphyritic hornblende-2-pyroxene andesite. Similar thick flows overlying volcano rudite are also exposed at 0028 and 0029 north of Wauko village, and in the stream south of Wauko (0024-26).

In Kak Creek, near Amde village on the northwest flank, porphyritic olivine-2-pyroxene basalt flows overlie folded dark Tertiary greywackes. Farther west in the main western stream are exposures of volcanic rudite, andesitic and basaltic lava (some of which is pyritiferous - 0030), and semi-consolidated volcanolithic boulder conglomerate (0031).

Exposures around the domes on the northern flank are poor, and most specimens were taken from stream or colluvial float. Specimens from the northeast flanks of the main dome are hornblende-2-pyroxene andesite and 2-pyroxene andesite (0004 - 6); those from the northwest flanks are hornblende-



To accompany Record 1973/89

B55/A14/48

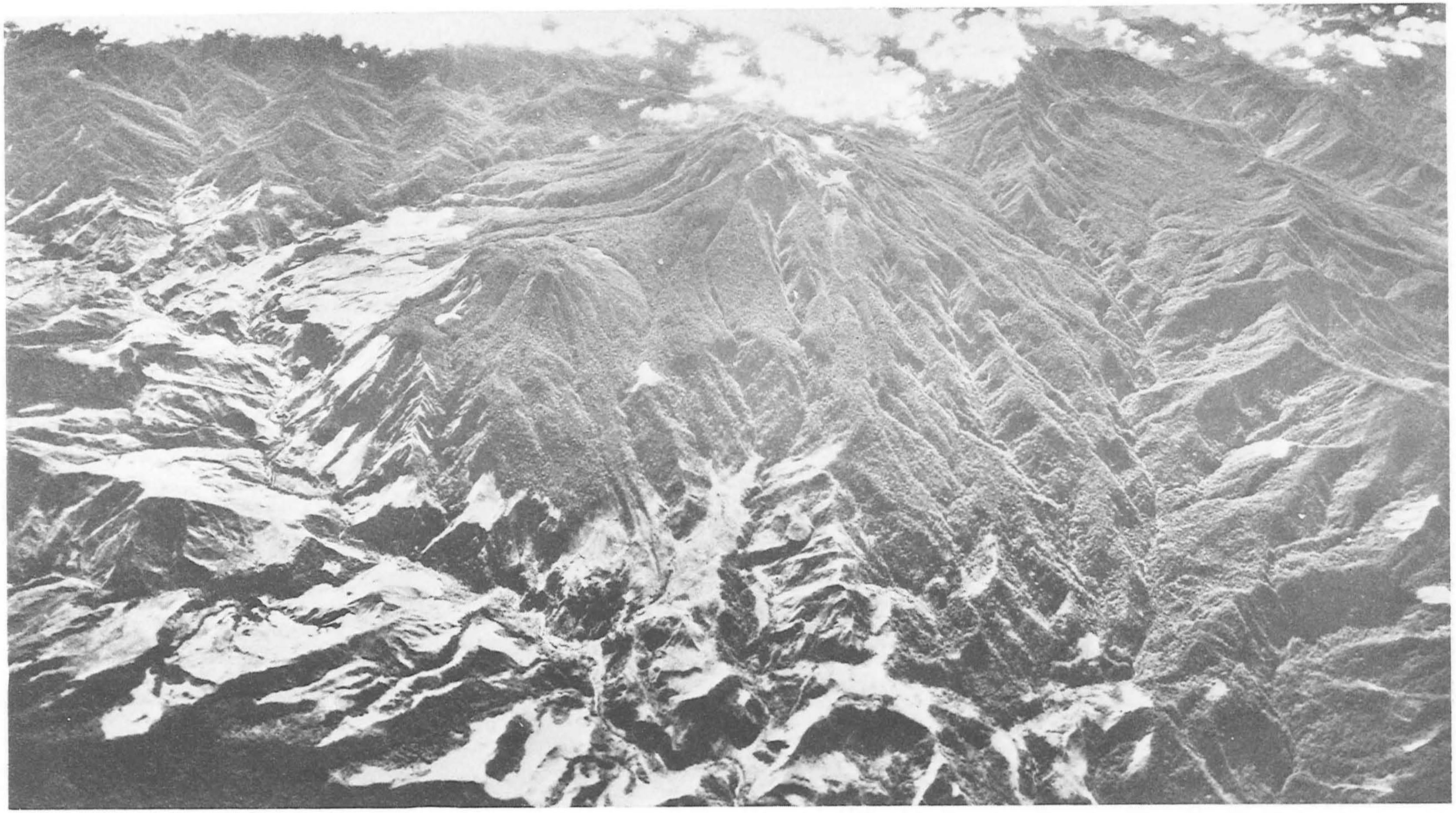


Figure 29. Mount Yelia and Marble Peak from the air, looking southeast. The main northern dome and its summit crater, the central dome complex, and the southern crater wall of Mount Yelia can be seen. The scarp-in-scarp structure of Marble Peak can also be seen (top right). In the left foreground is the Vilolo River. Photograph by the RAAF, 1949; the camera was tilted about 5 degrees to the right.

Figure 30. Main northern dome of Mount Yelia from Marawaka airstrip. The main cone is obscured by cloud at left, and on the right flank of the dome is a smaller dome. Neg. GA/5455.

Figure 31. Part of southern crater wall, Mount Yelia, and Marble Peak from the coulee (Fig. 29). White area at left centre is solfataric; to its left is part of small summit dome. Neg. GA/5460.

bearing 2-pyroxene andesite (0007) and olivine -)2-pyroxene andesite (0009). A specimen (0008) which probably originated from the smallest dome is a glassy hornblende-bearing 2-pyroxene andesite similar, apart from the glass content, to 0007.

Summit area

The southern crater wall is made up of 2-pyroxene-hornblende andesite flows and agglomerate. Almost identical rock types occur in the rudite at 0002 low on the northeastern flank. The andesites in the crater wall are slightly to strongly oxidized and jointed, and form extensive talus piles at the base of the scarp. Some of the rocks are pyritiferous.

The cumolodome near the southern crater wall is made up of slightly to moderately oxidized 2-pyroxene-hornblende andesite.

Outcrops of weathered hornblende-bearing andesitic rocks are abundant on the central dome and crater complex. There is also some 2-pyroxene-hornblende dacite in the vicinity of the survey marker (0017).

Marble Peak was sampled in only one place - close to the summit survey point. The specimen is a high-potash olivine-bearing low-silica andesite from a series of a large number of northeasterly dipping flows.

PETROGRAPHY

The lavas of Mount Yelia are dominantly porphyritic hornblende-2-pyroxene or 2-pyroxene-hornblende andesites (depending on the amount of hornblende), composed of phenocrysts of plagioclase, hornblende, and minor pyroxene in a fine-grained groundmass of plagioclase, augite, hypersthene and magnetite. Some rocks contain appreciable amounts of tridymite; these grade into dacite. Minor and accessory minerals include potash feldspar, apatite, ilmenite, and pyrite. The average estimated modal composition is

plagioclase	70 to 75 percent
hornblende	10 to 12 percent
augite	5 to 10 percent
hypersthene	3 to 5 percent
magnetite	6 to 7 percent

One specimen from the southern crater wall contains no hypersthene. Some contain only a trace of hornblende, the bulk of it having been replaced by pyroxene, magnetite, and plagioclase; others contain up to 18 percent. Augite ranges between 5 and 20 percent, and hypersthene reaches 7 percent. Tridymite occurs in about half the specimens of andesite, ranging from trace amounts to 5 or 7 percent.

The dacite is similar to the andesite but contains less pyroxene, and up to 10 percent modal tridymite. One specimen contains a trace of relict olivine.

Basalt and andesite in the Kak Creek area consist of plagioclase, augite, minor hypersthene, and rare olivine phenocrysts in a groundmass of plagioclase, augite, magnetite, hypersthene, and minor potash feldspar. One specimen has a trace of relict hornblende now almost all converted to fine-grained pyroxene, magnetite, and plagioclase. These rocks are high-potassium types transitional between the hornblende andesites typical of Mount Yelia and the high-K olivine basalts, or shoshonites, typical of most of the other Highlands volcanoes.

The single specimen from Marble Peak is a high-K low-silica andesite, made up of large (up to 5 mm, av. 2-3 mm) weakly zoned plagioclase phenocrysts, and a few augite and olivine phenocrysts in a groundmass of plagioclase laths, augite granules, small partly altered olivine crystals, potash feldspar (3-5%), magnetite, hypersthene needles, and apatite. There is a pronounced alignment of plagioclase phenocrysts and groundmass laths.

Plagioclase in all specimens forms subhedral to euhedral phenocrysts 0.5 to 5 mm long, generally with strong normal and oscillatory zoning; some phenocrysts are composite or clumped together. The phenocrysts range from free to packed with inclusions, with wide outer or core zones densely packed with fine-grained opaque-rich groundmass or glassy inclusions. In the more weathered specimens there is appreciable alteration along fractures concentrated in the cores of phenocrysts. Composition is generally andesine-oligoclase, with labradorite or even bytownite cores in some large phenocrysts. Groundmass laths are andesine-oligoclase. Potash feldspar rims are rare and extremely narrow.

Basaltic hornblende forms subhedral to euhedral phenocrysts and minor small groundmass crystals. The degree of oxidation to fine-grained, dark pyroxene-magnetite-plagioclase aggregates varies independently of other features of the rock from rims less than 0.01 mm wide to almost complete replacement. Pleochroism is generally:

α =pale yellow-brown, bright yellow, or pale greenish yellow-brown.

β =deep yellow-brown, dark brown, or greenish yellow-brown.

γ =extremely dark greyish brown, very deep intense red, reddish orange, dark greenish brown, or dark yellowish brown.

Zoning is weak to strong, generally oscillatory, and best seen in sections normal to α. In one specimen, the intense red hornblende is locally a very dark olive green or green-brown colour around fractures.

Augite occurs as small phenocrysts, which are commonly clumped together, groundmass prisms and needles, and mantles or fringes on hornblende. The phenocrysts range up to 1.5 mm, but are generally about 0.5 mm, and are faint green or brownish green. Zoning is common: in some specimens they are zoned from pale green to greenish brown at the rims, and appear to be highly oxidized - this is a common feature of rocks from the southern crater wall. Groundmass crystals are faint to pale green or yellowish-green, or, in some rocks from the southern crater wall, greenish brown. Clumps of small augite crystals with magnetite, plagioclase, and, rarely hypersthene are common in rocks with highly oxidized hornblende or relict olivine. They probably represent completely reacted hornblende or olivine crystals. Augite also forms fringes of acicular crystals aligned parallel to the c-axis on hornblende phenocrysts, and narrow rims, commonly on the larger faces only, of some hypersthene crystals. Rarely, augite is mantled by hornblende.

Hypersthene occurs as small prisms and microlites or needles in the groundmass, and in small quantities (trace to 4% of the rock) as small phenocrysts. The phenocrysts are long euhedral prisms, weakly pleochroic, and commonly have partial or complete augite mantles. They commonly form clumps with or without augite.

Magnetite forms small microphenocrysts and clumps of microphenocrysts 0.1 to 0.6 mm in diameter, and smaller euhedral crystals in the groundmass. It also forms part of the rims on hornblende and olivine, or the pyroxene-plagioclase-magnetite aggregates after hornblende and olivine.

Tridymite occurs as small rounded to irregular patches of radiating wedge-shaped or polygonal crystals. The polygons are probably cross-sections of the wedge-shaped crystals. In one of the dacite specimens, tridymite is either vug-lining, or has largely been plucked out during grinding of the thin section, or perhaps both.

Olivine occurs in trace to minor amounts (up to 3%) in several specimens from Kak Creek around the largest northern dome, and in the dacite from near the survey marker (0017). In all cases it is corroded and has either pyroxene (mainly orthopyroxene) - magnetite, pyroxene-magnetite-hornblende, hornblende, or magnetite rims, or composite pyroxene-magnetite beneath hornblende mantles.

Potash feldspar occurs in the most basic and most of the olivine-bearing specimens as very narrow rims on groundmass and some phenocryst plagioclase.

Apatite is similar to that in the Hagen andesites.

β-quartz occurs in one specimen (0006) as an 0.6 mm - wide square section with slightly rounded corners and a few fractures. Quartz inclusions were seen in a few specimens; they have pyroxene-rich reaction coronas.

CHEMISTRY

Morgan (1963) analysed specimens that were collected from Mount Yelia by Mr G. Rosenberg of the Division of National Mapping in 1963, and published one of the analyses (Morgan, 1966). The rocks are normal island-arc calc-alkaline andesites except for a slightly high potassium content, and contain around 15 percent normative free silica.

DISCUSSION

Mount Yelia is clearly different from the other Highlands volcanoes farther west in that it has erupted rocks of dominantly calc-alkaline affinity. Some olivine-bearing high-potash lavas are associated with the large northern dome (or cone?); the specimen from Marble Peak has definite high-potash characteristics, but this belongs to an earlier phase of volcanism. If the lavas of Marble Peak are dominantly high-K olivine basalt and andesite, then the Marble Peak-Mount Yelia pair may represent a parallel to the basement olivine basalt and central andesitic complex of Mount Hagen.

Because of the coldness of the fumarolic and solfataric areas and the rarity of seismic activity in the area, it is considered unlikely that Mount Yelia will erupt in the near future. However, the possibility of eruptions in the more distant future cannot be discounted. Therefore, a continuous recording seismograph is to be established on Mount Yelia, close to the Marawaka Sub-district Office. This device will record any seismic disturbance in the area and should provide early warning of any major volcanic activity.

An eruption would most likely be of the explosive-nuée ardente type, and the main dangers to life and property would be on the northeastern and northwestern flanks. The large avalanche valley on the northeastern side of the summit could again serve as a channel for avalanches and nuées ardentes, and these would endanger the Wauko villages, the villages 2 km southwest of Marawaka, and perhaps Marawaka itself. Eruptions down the southwestern side would seriously endanger the villages near Kak Creek, and possibly Amde village.

GENERAL DISCUSSION

Age of the volcanoes

Isotopic dating of two specimens of hornblende andesite from Mount Hagen yielded ages of 204 000 and 218 000 ± 10 000 years before present (R.W. Page, pers. comm., 1972). An age of 850 000 years was obtained from olivine basalt near the Tagari River (Williams et al., 1972); the lava probably came from Mount Kerewa or a small related centre to the west (Mt Iumu). There is evidence on Mount Giluwe of interglacial volcanic activity about 23 000 years ago, and a suggestion of even more recent activity from parasitic cones (Blake & Löffler, 1971). C. Pain and R. Blong (pers. comm., 1972) have concluded that the last major ash eruption from Mount Hagen was about 25 000–30 000 years ago on the basis of dates from ash beds. They also have obtained dates of between 18 200 ± 300 years and 200 ± 60 years from ash beds in the Wahgi Valley near Mount Hagen. These ashes may have come from Doma Peaks, or possibly Mount Yelia. A date from Mount Karimui east of Mount Ialibu is 202 000 ± 11 000 years (R.W. Page, pers. comm., 1973).

These data, together with the present fumarolic and solfataric activity on Mount Yelia and Doma Peaks, and the legends of eruptions from Doma Peaks indicate or suggest that volcanic activity began 850 000 or even 1 million years ago and has continued in some centres until the recent historical past.

Petrogenesis

Mackenzie & Chappell (1972) discussed the origin of the Highlands volcanoes, based on major and trace element analyses of specimens from Mounts Hagen, Giluwe, Ialibu, Suaru, Karimui, Kerewa, Bosavi, and Murray, and Crater Mountain. They suggested that the shoshonitic magmas originated in the mantle from sinking blocks of quartz eclogite which had become detached from the base of the downwarped thick continental crust underlying the volcanoes. Enrichment in potassium and other incompatible or volatile elements was caused by a zone-refining process as bodies of magma rose through a low-velocity zone containing a small amount of interstitial melt rich in these elements. The andesites were regarded simply as more siliceous, relatively less potassium-enriched magmas from the same source.

Subsequent field work, particularly on Mount Hagen, indicates that the andesites are later than the shoshonites, and appear to be derived from them by crystal fractionation, under conditions of increasing silica and water activity, and decreasing oxygen activity. This leads to the formation of plagioclase-rich, silica-oversaturated high-potash andesite and rare dacite which contain hornblende. The hornblende becomes more abundant and tends to be less oxidized (greener), and the degree of conversion to pyroxene and magnetite decreases with increasing silica content. However, the chemical data of Mackenzie & Chappell (1972) show that potassium content does not increase systematically with increasing silica content. Thus simple removal of olivine and augite phenocrysts, while it explains increasing SiO_2 and Na_2O, and decreasing MgO and CaO, does not explain the potassium concentrations. This can only be explained in a crystal fractionation model by removal of a potassium rich phase; the only plausible possibility is a potassic plagioclase, as plagioclase is an abundant phenocryst mineral.

There appears to be a direct relationship between the abundance and size of phenocrysts in the shoshonites of each volcano, and the volume and silica content of the andesites. This lends further support to the crystal fractionation hypothesis for the origin of the andesites, for a magma rich in large crystals would be much more prone to crystal settling fractionation than one with only a few small crystals.

Detailed geochemical studies aimed at determining the origin of the shoshonitic magmas and the relationship between them and the high-potash andesites is in progress.

Origin of crater and caldera-like features

Mount Hagen. The two southern caldera-like features appear to be intersecting simple sub-circular or elliptical collapse calderas which have been eroded away on their western sides. On the northernmost cone are at least two simple craters which have been breached on their western sides, deepened considerably and enlarged slightly in diameter by amphitheatre-headed gorges.

Doma Peaks, Mount Kerewa, and Mount Duau. The large C or U shaped outer escarpments of Doma Peaks and Mount Duau and the 'crater' wall of Mount Favenc may be trapdoor-like collapse calderas of the type proposed by Ridley (1971) for some of the Canary Islands volcanoes. The Lema-Ambua escarpment of Doma Peaks may be of similar origin, though it is more likely to be the result of prolonged erosional enlargement of a summit crater. The craters of Mount Bosavi and Mount Murray appear to be simple summit craters greatly enlarged by erosion. The caldera-like structures have probably also been enlarged by erosional retreat of the original escarpment.

Asymmetrical erosion of Mounts Bosavi, Murray, Duau, and Favenc may be due to orographic rainfall concentrated on the sides of the mountains which face the rain-bearing southeasterly trade winds. On each of these volcanoes, erosion is deepest and the crater or caldera is breached on the southern or southeastern side. Initial erosion would have been more rapid, and the crater or caldera would be first breached by one of the streams on the windward side. After breaching, rapid erosion of the crater could lead to the marked asymmetry of these volcanoes.

The westward-opening craters or calderas, or both, of Doma Peaks and Mount Kerewa and the much deeper erosion of the western slopes of Doma Peaks and the southern slopes of Mount Kerewa may also have been at least partly caused by similar orographic rainfall effects. However, the climatic behaviour in this area is complicated by local highland valley circulations (Brookfield & Hart, 1966), and the normal direction of the rain-bearing winds is uncertain. The style of erosion of the Highlands volcanoes is further discussed by Ollier & Mackenzie (in press), who describe in detail Mounts Bosavi, Murray, and Karimui.

Economical potential

It is widely recognized that porphyry copper deposits are associated with potassium-rich intermediate to acid high-level intrusive rocks in which there has been potassic alteration (Titley & Hicks, 1966; Rose, 1970). Such intrusive rocks are found in young mountain belts, such as the Andes, or in island arcs. The deposits consist of a central K-feldspar-biotite alteration zone with a high copper sulphide content, surrounded by a zone of quartz-sericite alteration with an increasing ratio of pyrite to copper sulphides outwards. There may or may not be a further outer zone of propylitic alteration (Rose, 1970).

Porphyry copper deposits which show some of these features are located at Panguna, Bougainville (MacNamara, 1968) and at Mount Fubilan (Ok Tedi - Bamford, 1972). The Ok Tedi deposit is associated with high-level stocks of quartz latite, monzonite, and syenodiorite-diorite. These are emplaced in a series of dark siltstones and thick limestone beds. There is extensive alteration or replacement by potash feldspar and biotite, and some quartz-sericite alteration associated with disseminated and massive sulphides, and magnetite complexes. At Panguna, all the types of alteration discussed by Rose are found, as well as extensive chloritic and quartz-kaolin-pyrite alteration.

There are several features of some of the Highlands volcanoes which are suggestive of porphyry copper deposits. Sulphur and sulphides (mainly pyrite) are exposed at the surface on Doma Peaks, Mount Yelia, and possibly Mount Bosavi. There is extensive chloritic, quartz-kaolin-pyrite, and some propylitic alteration in the eroded crater floor of Mount Murray, and some of the intrusive andesitic rocks contain droplets of magmatic copper sulphides.

There is also some propylitic alteration in Mount Bosavi. The potassium-rich andesitic and dacitic intrusive rocks exposed in Mount Murray, Mount Hagen, and Mount Bosavi are similar to some of the less altered intrusive rocks found at Ok Tedi and Bougainville. The sedimentary rocks beneath Mount Murray, Doma Peaks, and possibly Mount Bosavi are similar to those at Ok Tedi. Limestone is rare or lacking beneath Mount Yelia, but the sediments are dark volcanolithic siltstone and sandstone which are calcareous in part, and probably similar in chemical composition to some of the rocks at Panguna.

Detailed geological and geochemical work on Mount Murray and possibly also on Mount Bosavi may be worthwhile. Doma Peaks and Mount Yelia are not sufficiently deeply eroded to warrant any further economic investigation.

ACKNOWLEDGEMENTS

R.W. Johnson was responsible for much of the organizational work, and a large part of the field work on which this report is based. Without his efforts, much of the work would not have been possible. He was assisted for part of the time by I.P. Sweet and D.S. Hutchison, whose participation is also gratefully acknowledged.

Thanks are due to the following people who assisted us with accommodation and with information on their respective local areas:

The Assistant District Commissioners at Mount Hagen (Ross Allen), Ialibu (T. Heughson), Tari (C. Warrillow, and later P. Baker), Marawaka (G.J. Williams), and Kikori (D.J. Hook).

The Patrol Officer at Erave (S.R. Pearson).

District Commissioner D.J. Clancy at Mendi.

Father Dominic McGuiness at Tigibi mission for his hospitality and selflessness.

Keith Briggs and the staff of Bosavi mission.

Thanks also go to Xavier and Del Chang, and Richard Carver of Mount Hagen for their hospitality.

The safe, capable flying of our helicopter pilot, Allan Chesters, was invaluable in most of our work, and the able assistance of Kevin Scott, field hand and camp manager, who accompanied the writer on several traverses, was much appreciated.

REFERENCES

AUSTRALASIAN PETROLEUM COMPANY LIMITED, 1961 - Geological results of petroleum exploration in western Papua 1937-1961. J. geol. Soc. Aust., 8, 1-133.

BAIN, J.H.C., MACKENZIE, D.E., & RYBURN, R.J., 1970 - Geology of the Kubor Anticline - central highlands of New Guinea. Bur. Miner. Resour. Aust. Rec. 1970/79 (unpubl.).

BAMFORD, R.W., 1972 - The Mount Fubilan (Ok Tedi) porphyry copper deposit, Territory of Papua New Guinea. Econ. Geol. 67, 1019-33.

BIK, M.J.J., 1967 - Structural geomorphology and morphologic zonation in the central highlands, Australian New Guinea; in JENNINGS, J.N., & MABBUTT, J.A. (eds), LANDFORM STUDIES FROM AUSTRALIA AND NEW GUINEA. Canberra, A.N.U. Press, 26-47.

BLAKE, D.H., & LÖFFLER, E., 1971 - Development of volcanic and glacial landforms on Mount Giluwe, Territory of Papua and New Guinea. Bull. geol. Soc. Amer., 82, 1605-14.

BRANCH, C.D., 1967 - Volcanic activity at Mount Yelia, New Guinea; in Short papers from the vulcanological observatory, Rabaul, New Britain. Bur. Miner. Resour. Aust. Rep. 107, 35-9.

BROOKFIELD, H.C., & HART, D., 1966 - Rainfall in the tropical southwest Pacific. Aust. Nat. Univ. Dep. Geogr. Publ. G/3, Canberra, ANU Press.

COOKE, R.J.S. (in prep.) - Minor volcanological investigations 1971-73. Papua New Guinea Geol. Surv. Note on Investigation.

GLASSE, R.M., 1963 - Bingi at Tari. J. Polynes. Soc., 72, 270.

JAKEŠ, P., & WHITE, A.J.R., 1969 - Structure of the Melanesian areas and correlation with distribution of magma types. Tectonophysics, 8, 223-36.

JOHNSON, R.W., MACKENZIE, D.E., & SMITH, I.E., 1970 - Short papers on Quaternary volcanic areas in Papua-New Guinea. Bur. Miner. Resour. Aust. Rec. 1970/72 (unpubl.).

JOHNSON, R.W., MACKENZIE, D.E., SMITH, I.E., & TAYLOR, G.A.M., (1973) - Distribution and petrology of late Cainozoic volcanoes in Papua New Guinea. THE WESTERN PACIFIC: ISLAND ARCS, MARGINAL SEAS, GEOCHEMISTRY. P.J. Coleman, ed. Univ. W. Aust. Press, 523-33.

JOHNSON, R.W., MACKENZIE, D.E., & SMITH, I.E., 1971 - Seismicity and late Canozoic volcanism in parts of Papua New Guinea. Tectonophysics, 12, 15-22.

LÖFFLER, E., 1972 - Pleistocene glaciation in Papua and New Guinea. Z. Geomorph., 13, 32-58.

MACKENZIE, D.E., 1970 - Petrology of Pleistocene volcanoes, New Guinea highlands. ANZAAS 42nd Cong., Port Moresby (Abstr., Sec. 3).

MACKENZIE, D.E., & BAIN, J.H.C., 1972 - Reconnaissance geology of the Baiyer River-Jimi valley area. Bur. Miner. Resour. Aust. Rec. 1972/35 (unpubl.).

MACKENZIE, D.E., & CHAPPELL, B.W., 1972 - Shoshonitic and calc-alkaline lavas from the Highlands of Papua New Guinea. Contr. Mineral. Petrol., 35, 50-62.

MACNAMARA, P.M., 1968 - Rock types and mineralization at Panguna porphyry copper prospect, upper Kaverong valley, Bougainville Island. Proc. Aust. Inst. Min. Metall., 228, 71-9.

MORGAN, W.R., 1963 - The petrology of lava samples from Mount Victory and Mount Yelia, Territory of Papua and New Guinea. Bur. Miner. Resour. Aust. Rec. 1963/160 (unpubl.).

MORGAN, W.R., 1966 - A note on the petrology of some lava types from east New Guinea. J. geol. Soc. Aust., 13, 583-91.

NOAKES, L.C., 1939 - Geological report on the Chimbu-Hagen area, Territory of New Guinea. Geol. Surv. T.N.G. (unpubl. ms.)

OLLIER, C.D., & MACKENZIE, D.E., - Subaerial erosion of volcanic cones in the humid tropics. J. Trop. Geog. (in press).

PERRY, R.A., et al., 1965 - Lands of the Wabag-Tari area, Papua and New Guinea. CSIRO Land Res. Ser. 15.

RICKWOOD, F.K., 1955 - The geology of the western Highlands of New Guinea. J. geol. Soc. Aust., 2, 63-82.

RIDLEY, W.I., 1971 - The origin of some collapse structures in the Canary Islands. Geol. Mag., 108, 477-84.

ROSE, A.W., 1970 - Zonal relations of wallrock alteration and sulphide distribution at porphyry copper deposits. Econ. Geol., 65, 920-36.

RUTHERFORD, G.K., 1968 - Observations on a succession of soils on Mount Giluwe, eastern New Guinea. Ass. Amer. Geogr. Ann., 58, 304-12.

TAYLOR, G.A.M., 1971 - An investigation of volcanic activity at Doma Peaks. Bur. Miner. Resour. Aust. Rec. 1971/137 (unpubl.).

TITLEY, S.R., & HICKS, C.L. (editors), 1966. GEOLOGY OF THE PORPHYRY COPPER DEPOSITS, SOUTHWESTERN NORTH AMERICA. Tucson, Univ. Arizona Press.

WILLIAMS, P.W., McDOUGALL, I., & POWELL, J.M., 1972 - Aspects of the Quaternary geology of the Tari-Koroba area, Papua. J. geol. Soc. Aust., 18, 333-47.