PHOTOGEOL OGY OF
VOLCANIC TERRAINS
with particular reference to
a photo-interpretation of
Western Vanua Levu, Fiji.

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The Department of Geology, Australian National University, Canberra.
Volcano and its beautiful landscape (Batur caldera and lake Batur)
INTRODUCTORY STATEMENT.

This M.Sc. thesis is based on a study of volcanoes, with particular emphasis on the aerial photograph expression of volcanic landforms. It is divided into three parts:

I. A general consideration of volcanism.

II. Morphological expression of volcanic features (with particular reference to aerial photograph interpretation).

III. A photo-interpretation study of western part of Vanua Levu, Fiji.

All the work reported on this thesis is my own work, unless otherwise acknowledged.

Sae'un HARDJOPRAWIRO
Canberra, March 1980
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It is with good reason that the writer wishes to end by acknowledging his debt of gratitude to his parents and to his wife.
This thesis records my study of volcanoes in the S.W. Pacific. It starts with a general review of the types of volcanic activity found in the region and its relationship to plate-tectonic geometry. The main purpose of the work was to study the photogeologic expression of different volcanic forms, and the characteristics of different types of young to deeply eroded volcanoes are set out in the second part of the thesis. Finally the experience gained was then applied to a detailed photogeological study of a varied volcanic terrain in western Vanua Levu (Fiji). The results, especially differences between the photogeology and published maps (1:50,000) were checked in the field. Some important revisions to the maps are suggested. The photogeological study includes an analysis of various lineament and volcano spacing. This indicates that the volcanic and structural features are controlled by repeated influence of crustal fractures in a 25 km thick crustal slab.
# CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTORY STATEMENT</td>
<td>i</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENT</td>
<td>ii</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF PLATES</td>
<td>x</td>
</tr>
<tr>
<td>I. A GENERAL CONSIDERATION OF VOLCANISM</td>
<td>1</td>
</tr>
<tr>
<td>IA. Volcanism and plate tectonics</td>
<td>1</td>
</tr>
<tr>
<td>a. Volcanism associated with collision zones</td>
<td>5</td>
</tr>
<tr>
<td>b. Volcanism associated with sea-floor spreading</td>
<td>5</td>
</tr>
<tr>
<td>c. Volcanism on the intra-continent and rift system</td>
<td>9</td>
</tr>
<tr>
<td>d. Late orogenic volcanism</td>
<td>9</td>
</tr>
<tr>
<td>e. Intra-oceanic plate volcanism over hot spots</td>
<td>11</td>
</tr>
<tr>
<td>IB. Volcanism in the South-West Pacific</td>
<td>11</td>
</tr>
<tr>
<td>1. Volcanism in Indonesian archipelego</td>
<td>12</td>
</tr>
<tr>
<td>2. Volcanism in Papua New Guinea</td>
<td>17</td>
</tr>
<tr>
<td>3. Volcanism in Australian continent</td>
<td>18</td>
</tr>
<tr>
<td>II. MORPHOLOGICAL EXPRESSION OF VOLCANIC FEATURES (with particular</td>
<td>25</td>
</tr>
<tr>
<td>reference to aerial photograph interpretation)</td>
<td></td>
</tr>
<tr>
<td>1. Volcanic centre recognition on aerial photographs and Landsat</td>
<td></td>
</tr>
<tr>
<td>imagery</td>
<td></td>
</tr>
<tr>
<td>2. Plateau basalts and their morphology</td>
<td>29</td>
</tr>
<tr>
<td>3. Shield volcanoes and their genesis</td>
<td>34</td>
</tr>
<tr>
<td>4. Strato-volcanoes or composite volcanoes</td>
<td>36</td>
</tr>
</tbody>
</table>
5. Craters, calderas, and maars associated with phreatic eruption... 40
6. Lava flows and their structures.......................................... 43
7. Dykes and eroded volcanic centres (infrastructures of volcano)... 49
8. Examples of photo-interpretation of Gilgandra NSW and Bagstowe complex Qld.......................................................... 51

III. PHOTOGEOLOGICAL INTERPRETATION OF THE WESTERN PART OF VANUA LEVU, FIJI.............................................................. 61
1. Introduction............................................................................. 61
   a. Remote sensing and geological mapping............................. 61
   b. Preparation for study..................................................... 64
   c. Previous work.................................................................. 69
2. Regional Structural Setting of Fiji........................................ 71
3. Photo-lithological unit description...................................... 81
   a. Preparation..................................................................... 81
   b. Photo-lithological unit description................................. 83
4. Structural analysis............................................................. 113
   a. Coastline analysis.......................................................... 113
   b. Photographic lineament analysis...................................... 116
   c. Drainage pattern analysis............................................... 122
   d. Faults............................................................................ 125
   e. Volcano-spacing analysis................................................ 130
   f. Structural interpretation of Vanua Levu............................ 144
5. Field checking..................................................................... 148
6. Conclusions......................................................................... 150
REFERENCES.......................................................................... 152
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The zonal arrangement of the Earth</td>
</tr>
<tr>
<td>2</td>
<td>Volcanic activity associated with convection currents in the Upper mantle</td>
</tr>
<tr>
<td>3</td>
<td>The relationship between continental, oceanic crusts and mantle</td>
</tr>
<tr>
<td>4</td>
<td>Map of the Pacific Ocean showing the &quot;andesite line&quot; and plate movement</td>
</tr>
<tr>
<td>5</td>
<td>The detail structure of Mid-ocean ridge</td>
</tr>
<tr>
<td>6</td>
<td>The rift valley genesis associated with convection current</td>
</tr>
<tr>
<td>7</td>
<td>Indonesian archipelago showing two arcs bending in the Banda Sea</td>
</tr>
<tr>
<td>8</td>
<td>Structural elements of Papua New Guinea</td>
</tr>
<tr>
<td>9</td>
<td>The main basement of Australia</td>
</tr>
<tr>
<td>10</td>
<td>Cainozoic volcanoes in eastern Australia</td>
</tr>
<tr>
<td>11</td>
<td>Deccan Plateau basalts, India</td>
</tr>
<tr>
<td>12</td>
<td>Ring Structure genesis of Odesa, U.S.A</td>
</tr>
<tr>
<td>13</td>
<td>Volcano lineament and volcano spacing of the Galapagos Islands</td>
</tr>
<tr>
<td>14</td>
<td>Flow tops structure</td>
</tr>
<tr>
<td>15</td>
<td>Columnar jointing growth in basaltic lava flow</td>
</tr>
<tr>
<td>16</td>
<td>Bottom structure of basaltic lava flow (spiracle)</td>
</tr>
<tr>
<td>17</td>
<td>Bottom structure of basaltic lava flow (pipe versicular)</td>
</tr>
<tr>
<td>18</td>
<td>Photo-Geological map of Gilgandra, N.S.W. Australia</td>
</tr>
</tbody>
</table>
19. Fig. 19 - Photo-Geological map of Gilberton, Qld, Australia........ 56
20. Fig. 20 - World index map showing position of Fiji..................... 60
21. Fig. 21 - Photo-index map of 1:40,000 scale photos, Fiji................. 62
22. Fig. 22 - Photo-index map of 1:80,000 scale photos, Fiji................ 65
23. Fig. 23 - Index of Landsat imagery, Fiji........................................... 68
25. Fig. 25 - Sea-floor spreading interpretation between New Hebrides
   and Fiji.......................................................... 72
26. Fig. 26 - The main structure elements of North Fiji Plateau.............. 74
27. Fig. 27 - The position of Fiji Plateau associated with the island
   arc systems........................................................ 77
28. Fig. 28 - Lithological distribution map of Vanua Levu...................... 79
29. Fig. 29 - Cross-section sketch of Ngaloa zone................................. 98
30. Fig. 30 - Rosediagram of coastline and Vanua Levu island axis............. 114
31. Fig. 31 - Rosediagram of coastline of Mbua area............................ 115
32. Fig. 32 - Sketches of lineaments manifested under stereo-pair............ 118
33. Fig. 33 - Rosediagram of photographic lineaments in Vanua Levu and
   Mbua area.......................................................... 121
34. Fig. 34 - Rosediagram of drainage pattern of Vanua Levu and Mbua
   area..................................................................... 123
35. Fig. 35 - Volcanic centre distribution in Vanua Levu......................... 126
36. Fig. 36 - Histogram of volcano-spacing in Vanua Levu....................... 134
37. Fig. 37 - Volcanic clusters of 56 centres in Vanua Levu.................... 135
38. Fig. 38 - Rosediagram of volcanic centre lineament of Mbua, Vutu-
   singa complex and Taveuni island........................................... 137
39. Fig. 39 - Rosediagram of fault interpretation of Vanua Levu and
composite rosediagram of coastline, drainage, photo-
lineament, volcano spacing analyses..................... 142

40. Fig. 40 - Fault map interpretation of Vanua Levu.................. 145

41. Map 1 - Photogeological interpretation of Mbua area.............. back pocket

42. Map 2 - Published geological maps of Mbua area on scale of

1:100.000............................................ back pocket
List of plates.

1. Plate 1: Volcanic centres obtained from Landsat of East Flores, Indonesia.................. 26
2. Plate 2: Crater growth, West Flores, Indonesia.................. 28
3. Plate 3: Cuestas formed by lava flows, Batur caldera, Bali, Indonesia.................. 37
4. Plate 4: Dykes in Gilgandra area, N.S.W., Australia.................. 54
5. Plate 5: Ring dykes in Gilberton, Qld, Australia.................. 55
6. Plate 6: Mbua conglomerate................................. 86/87
7. Plate 7: "Bubbly" morphological feature of Mbua conglomerate viewed stereoscopically............... 90
8. Plate 8: "Hornito" and Ravuravu Lake................................. 96
9. Plate 9: Mbenutha breccia........................................ 100
10. Plate 10: Mbenutha clasts........................................ 103
11. Plate 11: Ndelanathau and "triangular facet".......................... 103
12. Plate 12: Natua Formation........................................ 108
13. Plate 13: The youngest Lambasa fault.............................. 124
14. Plate 14: Volcano spacing of Vutusinga complex...................... 138
15. Plate 15: Synclinal interpretation in Naurore Bay...................... 143
List of Table.

1. Table 1 - Volcano classification .................................................. 30
2. Table 2 - The differences between craters and calderas ............... 39
3. Table 3 - List of photos on 1:40,000 scale ................................. 63
4. Table 4 - List of photos on 1:80,000 scale .................................. 66
5. Table 5 - List of Landsat imagery covering Fiji ............................ 67
6. Table 6 - Stratigraphic column for Vanua Levu ............................... 80
7. Table 7 - Photo-lithological rock units ........................................ 82
8. Table 8 - Coordinates of volcanic centres ..................................... 127
9. Table 9 - Lineament lengths in 10° intervals ................................ 128
10 Table 10 - Volcano-spacing .......................................................... 131
11 Table 11 - Proportion of lineaments obtained from coastline, photo-
   lineaments, drainage pattern, and volcano-spacing
   analyses ........................................... 139
12 Table 12 - Efficiency of aerial photo of different scales ............... 147
A GENERAL CONSIDERATION OF VOLCANISM.

A. Global setting of volcanoes.

The advances of seismic studies have revealed the zonal arrangement of the Earth's mantle and crust, and support a division of the upper mantle into asthenosphere and lithosphere. The crust and lithosphere float on the asthenosphere in six major plates building the Earth's shell.

The thickness of the crust and lithosphere varies due to isostatic adjustment. Under the oceans, crust and lithosphere are 6 km and 70 km respectively, but under continents the crust is about 30 km to 55 km and the lithosphere is thicker than 150 km (Fig. 3.). The boundary between lithosphere and asthenosphere is defined by a marked reduction in seismic velocity and the asthenosphere corresponds to a Low Velocity Zone (LVZ). It is thought that the mantle is partially melted in this zone. The upper mantle which is thought to be solid, grades into lower mantle at about 700 km (Fig. 1.).

Volcanic activity is probably initiated in the asthenosphere where magmas are generated, and the processes operating to govern composition, timing and spacing of resulting volcanoes, is of great importance to this study. Essential energy resulting from convection currents and radioactive decay, govern plate tectonic processes (eg. subduction zone, hot spots, partial melting and so on) and magmas rise through fractures that reach the Earth's surface forming volcanoes in different
Fig. 1 — Diagram illustrating the zonal arrangement of the Earth derived from seismic studies (Modified from McDonald, 1970 and Holmes, 1972).
The Earth’s crust which consists of continental and oceanic portions, has variable thickness. The thickness of the continental crust ranges between 30 km to 55 km (Wyllie, 1972). The thickest continental crust is found under the mountain ranges, where the continents have collided to form a double crustal layer, e.g. Himalayan and Alpine ranges. Such thickened crust rises rapidly under isostatic adjustment. The continental rock composition ranges from granitic to gabbroic rocks.

The boundaries between continental and oceanic crust are interpreted from gravity anomalies within a transition zone or fore-arc (Dewey and Bird, 1970). In the Pacific Ocean the continental and oceanic crusts are separated by subduction zones marked by the "andesite line" (Fig. 4).

The crust composition influences the composition of magmas erupted through the crust. Sometimes crustal fragments can be found as xenoliths in the lava flow or melted to form a new lava composition with zonal structure. Thus the different volcanic rock composition are not only caused by fractionation processes, but they are also caused by crustal composition.

Continental separation is now well established by several geological and geophysical criteria. According to plate tectonic theory the globe is divided into six major plates, the boundaries of which are marked by major linear belts of seismic activity, called "plate margins".
Fig. 2 — Diagram illustrating volcanic activity associated with convection current in the Upper mantle.

a = amphibolites, b = basalts, e = eclogites, B = Oceanic crust, M = Moho discontinuity, LVZ = Low Velocity Zone, thick arrows = relative movement of the plates, arrows indicate convection currents in the asthenosphere, double arrows = addition heat. (Modified from Green, 1972; Ringwood, 1974; and Bullard, 1976)
The boundary between two plates might show an extensional or compressional manner.

Volcanism associated with extensional or compressional conditions and in addition intra ocean and intra continent activity may occur. The volcanism formed by these types will be discussed as follows:

a. Volcanism associated with collision zones (Tazieff, 1974).

The plate margin collisions can occur between continental to continental crusts, or continental to oceanic crusts, or oceanic to oceanic crusts. The collision zones or compression zones or destructive zones between oceanic and continental crusts, where the oceanic crust is subducted into the mantle, is characterized by island arc volcanoes, eg. Indonesian island arc, Japan island arc and New Zealand. Volcanic rocks produced in these types of island arc range between calcic to calc-alkaline andesite, tholeiitic basalt to shoshonite or alkaline basalt.

Collision between continental and continental crusts produces volcanic rocks with compositions of high-K calc-alkaline andesite to calc-alkaline rhyolite and their plutonic equivalents. Himalayan and Alpine type volcanism has related to late orogen development and its activity has ceased since the Tertiary.

b. Volcanism associated with sea-floor spreading zones.

Volcanism at sea-floor spreading zones or extension zones where
Fig. 3. Diagram to illustrate the relation between continental, oceanic crust and mantle; 1 = Oceanic crust; 2 = Transition zone; 3 = Lithosphere; 4 = Relative movement of the slabs; 5 = Continental crust; 6 = Asthenosphere (Modified from Dickinson, 1974; Stewart & Poulet, 1974; Dietz, 1972; and Ringwood, 1974) M = Moho
the oceanic crusts are being continuously created along the mid-ocean ridges by direct convective upwelling (Fig. 5), produces basaltic rocks. It is thought that these volcanic rocks are derived directly from upper mantle materials (Ringwood, 1974), in which pyroxene and olivine minerals dominate.

Studies in the Atlantic and Pacific areas, indicate spreading rates of 1 to 4 cm year$^{-1}$ for each limb of the mid-ocean ridge. By considering that the spreading rate remained relatively constant, all the major oceans are less than 500 to 200 million years old.

The mechanism of sea-floor spreading maintains the continental separation and plate tectonic movements. The rate of sea-floor spreading is generally considered to balance the rate of subduction, this means the Earth has maintained its radius since the sea-floor spreading began. Sea-floor spreading might change its position and direction or times of activity, so that ridges of extinct sea-floor spreading can be found as a "fossil", eg. Kuala-Pacific ridge and the Philippines ridge in South Asia (Ben Abraham, 1978). The lack of seismic activity indicates that the production of new oceanic crust has ceased. This interpretation is based on the studies of rock composition associated with modern sea-floor spreading zones.

Volcanism is not generally associated with transform faults, that offset the mid-ocean ridges. Volcanism might occur on the transform faults within the continent (Papua island (?)).
Fig. 4 - Map of the Pacific Ocean showing the "andesite line" and plate movements. (Black areas have heat-flow value $>3$; After Holmes, 1970; McKenzie & Richter 1976).
c. Volcanism on the intra continent and rift system.

The mechanism of intra continental volcanism can be explained by some forms of convection hypothesis (McKenzie & Richter, 1976) (Fig. 6). Convection currents in the Low Velocity Zone move upward and turn laterally when they strike against the base of the lithosphere. Some fractures are developed (extension zones) in both the lithosphere and crust. The resulting rift systems and graben structures adjust as blocks under gravity (e.g. the vast and long graben in East Africa, Rhine Graben and Lake Baikal). The magmas formed by partially melted mantle in the Low Velocity Zone, penetrate the lithosphere and continental crust to produce contaminated magmas (Harris, 1970).

The Deccan Plateau in India formed from basaltic magma that penetrated through fractures resulting from the collision between Asiatic and Indian plates (Holmes, 1970).

d. Late orogenic volcanism.

Orogenic volcanism follows the pattern of that described for island arcs and cordilleran situations, but volcanism is again active during the late stages of orogenesis. Orogenic activity with companion overthrusting is followed by uplift movements on block faults, accompanied by basalt-rhyolite magmas of alkaline affinity (Dietz, 1962; Spencer, 1974).

Late orogenic activity usually extends over vast areas, and magmas form batholiths with complex structures, because of repeated activity.
Fig. 5 — Diagram illustrating the detail structure of Mid-ocean ridge (Modified from Ringwood, 1972).

Fig. 6 — Diagram to illustrate the rift valley genesis associated with convection currents. A = rising convection current; A' = extension zone on lithosphere; A'' = fractures on the continental crust; B & C = going down currents; B' & C' = compression zones of Eclogite formation. (Modified from Holmes, 1972)
Small plutons of granite and new volcanoes erupted by cauldron subsidence are also associated with late orogenic activity, for example the Late Devonian volcanoes in Victoria, Australia. The cauldron subsidences are characterized by ring dykes and different composition of volcanic rocks can be explained by bimodal volcanoes formed during space and time fractionation of magma.

e. Intra ocean plate volcanism over hot spots.

Volcanism in this zone results from fissure-type eruptions through the fractures which formed by upwelling convection currents, then the eruption becomes central, because the lava flow blocks part of the fissure. It begins as submarine volcanoes but some reach sea level and others become extinct and sink to form "guyots".

Hawaiian volcanoes have a height of about 9.14 km (4.2 km above sea level) above the ocean floor, and a width of about 112 km in diameter. These volcanoes are composed of calc-alkaline to tholeiite basalt derived directly from upper mantle material. The water present in the mantle reduces the melting point of the oceanic crust (Ringwood, 1974). The thickness of the oceanic crust below the Hawaiian volcano is thought to be 6 km and depth of the magma source might be over 150 km.

B. Volcanism in the South-West Pacific.

The Southwest Pacific regions are of particular interest to this
discussion. Volcanism associated with subduction zones in which some of them have ceased, will be discussed.

The Southwest Pacific lies at the junction of the Indo-Australian plate, the Pacific plate and the Asian plate. The boundary between the Indo-Australian and Asian plates is a seismic and volcanic orogenic zone extending from the Himalayas through the Indonesian archipelago, bending into the Philippine arc. The Indo-Australian plate is thought to subduct under the Asian plate and forms a trough and island arcs, whereas the boundary between the Pacific and Indo-Australian plates forms a volcano chain and trench which run from the Papuan mainland to the Macquarie triple junction. A transform fault along the north coast of West Irian is the continuation of the subduction zone in New Britain.

Volcanism formed by the collision of these three plates is the main subject to discuss in this chapter and the discussion will be begun from the western part of the Pacific or Indohesian archipelago.

B.1. Volcanism in the Indonesian archipelago.

The Indonesian archipelago consists of more than 3,000 islands. They formed mainly from volcanic materials. All the big islands (Sumatra, Java, Kalimantan, Sulawesi and West Irian) at least have volcanic centres, lava flow and volcanoclastic beds.

Sumatra, Java, Sunda islands (Bali, Lombok, Flores, Sumbawa) and
Sulawesi have active volcanoes, some of them regarded as destructive if they erupt. Kelud volcano in East Java for example is the most dangerous one, because it has a crater lake at its summit; the lake water mixing with hot pyroclastics forms hot lahars which flow long distances destroying all in their path. The water level in the crater lake is now kept low by tunneling.

The volcanic activity in the Indonesian archipelago can be divided into two areas, eg. a western part including Sumatra, Java and Sunda Besar islands, and an eastern part with complicated tectonic structures and movements (Fig. 7).

The volcanoes in the western part of Indonesia are formed by the partial melting of continental crust in which calc-alkaline to tholeiitic andesites have been produced. The Benioff zone dips northwards at 40° to 60°. Hutchison, 1973 found that the K content increases with the depth of the Benioff zone. Now the volcanoes are active above the 100 to 200 km depth Benioff zone. The active volcanoes running from Burma down to Sumatra, Java and Sunda Besar islands, form two arcs. The inner volcanic arc has positive gravity anomalies and can be traced from Sumatra to Flores continuously, whereas the outer arc or fore-arc which consists of troughs and sporadic islands (structural high), has negative gravity anomalies (Fig. 7). The outer arc ends at Sumba island, in which Audley Charles (1975) interpreted that the trough to be cut by Sumba fractures running from West Australia (Westralia geosyncline) to Sulawesi. From this point the two arcs then curve.
Fig. 7 — INDONESIAN ARCHIPELAGO showing volcanic and anomaly arcs bend in the Banda Sea. 1 = Volcanic arc, 2 = Zone of negative anomalies, 3 = Transform fault, 4 = Subduction zone.
to the west under Banda island and form complicated structures.

Some geologists interpret that the western part of Indonesia was formed by a single orogen, of which Anambas-Schwanner Mountain belt in Kalimantan was the primary geanticline formed in Permo-Carboniferous. The orogenic migrations are toward southwest and northeast from the primary geanticline. The present orogen is marked by active volcanoes along the inner arc.

In the eastern part of the Indonesian archipelago the volcanic belts are very complicated, because at least three force components are working on it. The Pacific plate moving westwards against the Asian plate which moves southeastward and the Indo-Australian plate moving northwards against the Asian and Pacific plates. The Sulawesi and Banda islands are thought to be at the centre of rotation between the three plates. In this area there are three belts of volcanoes, eg. Banda belt, Sulawesi belt and Halmahera belt.

Consensus on the geological structure and history of the eastern part of Indonesia has not been reached among geologists. For example in Timor there are two types of lithology, eg. sedimentary rocks associated with deep sea mixed with volcanic rocks associated with island arc. The sedimentary rocks are related to West Australian basin stratigraphy.

Some calc–alkaline basalts have been found in Indonesian islands and
Fig. 8 Structural elements of Papua New Guinea. 1 = Fly platform, 2 = Papuan fold belt, 3 = New Guinea mobile belt, 4 = Quaternary Sepik–Ramu Basin, 5 = Papuan ultramatic belt, 7 = Kubor anticline, 6 = Ramu–Markam fault zone, 8 = Subduction zone, 9 = Relative motion of plate (After Bain, J.H.C, 1973 and Johnson, R.W. 1976).
they are used to interpret the existence of subduction zones in the Sunda shelf history, eg. Meratus ridge in Kalimantan and Malili areas in the southeastern arm of Sulawesi (Katili, 1978).

B.2. Volcanism in Papua New Guinea.

Papua New Guinea is part of a tectonically active and complex region between the Pacific and Indo-Australian plates. During the late Cainozoic and concurrently with tectonic activity, volcanism took place in widely separated areas, producing clusters of volcanoes, such as the Highland, and narrow arc-like chains of volcanoes in New Britain and Bougainville islands.

The Highland volcanic cluster can be divided into two groups of volcanoes (Johnson, 1973), eg. the Highland and the East Papuan volcanoes. The Highland volcanic clusters are made up of calc-alkaline and shoshonite rocks, and are formed in the Papuan fold belt, New Guinea mobile belt, and Neogene Cape Vogel Basin, where intensive faults and folds formed during tectonic activity (Fig. 8).

The island arc-like chain of volcanoes can be separated based on subduction zone direction and the time of activity. Two main directions of subduction zone identified, eg. east-west curving to northeast (New Britain), and northnorthwest - southsoutheast (New Ireland to Bougainville and Solomon islands.
Bain, 1973 suggested that the New Britain island arc consists of two arc volcanoes, the Paleogene island arc occupying the southern part of New Britain Island and Quaternary island arc occupying the Middle and northern part of New Britain, and it is continued westward on the mainland coast of Papua New Guinea. These areas are characterized by active volcanoes made up by calc-alkaline to tholeiitic andesite rocks, Johnson (1973) called this area the Bismark island arc.

The K content progressively increases northwards, it suggests that the Benioff zone dips northward between 60° to 80° (Johnson, 1973); the eastern part of this subduction zone is nearly vertical.

The second arc is an outer arc which runs from New Ireland, Bougainville and the Solomon islands. This can also be divided into two arc systems, eg. Paleogene and Quaternary arc volcanoes. The rocks range from calc-alkaline andesite to dacitic composition, and the Benioff zone dips northeast at 45° to 60° (?).

c. Volcanism on the Australian continent.

The Australian continent can be divided into three main domains, the Pilbara-Yilgarn, the Arunta-Gawler and the Tasman domains, (Fig 9).

Volcanism in the Pilbara-Yilgarn and Arunta-Gawler domains was caused
Legend figure 9.

1. Boundary of major province.

2. Boundary of sub-provinces and zones therein.


4. Tertiary volcanoes.

5. Direction of younging of plutonism.


7. Axis of elongate basins on margins of Amadeus Transverse zone.

8. Limit of Tasman Paratectonic Zone.
Fig. 9. The main basement of Australian continent.
by intra-continental depression rather than plate margin tectonism (Duff & Longworth, 1974). On the stable domains, where the kratonization process has ceased, volcanism can occur over hot spots. The hot spots might originate in the asthenosphere below the lithosphere carrying the kraton.

Volcanism in the Tasman domain can be divided into three episodes, Paleozoic volcanism associated with inferred magmatic arcs, Mesozoic volcanism caused by partly magmatic arc, tension zones, and crustal movement, and Cainozoic volcanism associated with hot spots and migration on extension zones.

Volcanism in the Tasman domain began in the Late Precambrian and was thought to be related to plate margin tectonism or magmatic arc (Solomon & Griffiths, 1972; Packham & Leitch, 1974; and Harrington, 1974). Harrington suggested that the older magmatic arc is the Nebine arc, which trends NNE. The composition of these magmatic arcs is the same as that in modern island arcs, ranging from tholeiitic to alkaline basalts.

The Paleozoic-Mesozoic magmatic arc activity in the Tasman geosyncline consists of two major parts, the Lachlan and New England. They are separated by the Permo-Triassic Sydney and Bowen Basins (Crook, 1969).

The Lachlan Fold Belt (magmatic arc) had been active since before the Lower Silurian when this area was at the pre-kratonic stage. There is no evidence of Early Silurian volcanism in eastern Australia (Crook, pers.
In the Middle Silurian to Middle Devonian volcanism occurred under tensional tectonics, whereas in the Late Devonian, volcanism associated with transitional tectonics is suggested (Crook, 1980). The volcanic composition of this area ranges from andesite basalt to dacite and rhyolite andesite (Branagan, 1969). The Lachlan Fold Belt was in the transitional tectonic stage in the Late Devonian, where basaltic volcanics might have been derived from "remnant" magma chambers in the upper mantle. Extensional rifts are characterized by bimodal associations of basalt and rhyolite (eg. Lochiel basalt and Eden rhyolite).

In the New England Fold Belt the magmatic arc had been active since before the Triassic when this area was at the pre-kratonic stage, but during the Triassic, it was at the transitional stage (Crook, 1980). Branagan (1976) suggested that volcanism during the Late Carboniferous and Early Permian in N.S.W., occurred in rift systems, where numerous basaltic rocks were injected through the faults directly from upper mantle. The magmatic arc at that time was located on the New England Fold Belt.

The Cainozoic volcanism in the Tasman Geosyncline is divided into three main provinces, Lava Field Province, Central Volcano Province and Aerial volcano Province (Wellman & McDougall, 1974; Branagan, 1969 and Ollier, 1978).

The Lava Field Provinces in which the lavas form an extensive field or in some places a lava pile up to 1.000 m thick, composed extensively.
of basalt. The eruption area is thought to consist of a diffuse dyke and pipe swarm up to 100 km across, which forms a shield volcano type. Examples of this province are Barrington, Liverpool and Monaro volcanoes. Lava Field Provinces appear to be closely associated with the main divide, and in Queensland they follow the divide rather than the coastal ridges (Ollier, 1978).

The Lava Field Province gets younger to the west, which means the active centres of the Lava Field volcanoes have migrated to the west by distances up to 200 km (Wellman & McDougall, 1974 and Ollier, 1978). Lava Field Province volcanoes were active between 55 and 34 m.y ago (Ollier, 1978).

Central Volcano Provinces in which the flows are predominantly basaltic, were extruded from well-defined vents. These materials commonly gave rise to large volcanoes and are distinguished by the presence of some felsic flows and felsic and mafic intrusions. Tweed volcano, Nandewar volcano, Canobolas volcano and Springsure volcano are included in this province (Fig. 10).

The Young ing southwestward of the Central Volcano Province (Crook estimated only one zone of young volcanoes trending SW), can be explained by the drifting northeastward of the Australian continent over magma sources fixed in the asthenosphere beneath the crust (hot spots, melting spots, plumes; Wellman & McDougall, 1974, and Ollier, 1978). The Central
Fig. 10 - Cainozoic volcanism in Australia. 1 = Nandewar volcano; 2 = Tweed volcano; 3 = Springsure volcano; 4 = Liverpool range; 5 = Newer volcanics. (After Weisman & McDougall, 1974.)
Volcano Province was active between 33 and 6 m.y ago.

Aereal Province (Also known as polyrifice volcanism) is characterized by the absence of any tendency for eruption centres to be located at definite points for any length of time (Ollier, 1978). Lava cones, scoria cones, maars are the dominant volcanic type and stratovolcanoes are absent or rare. The spatial distribution of volcanoes is irregular, with some clustering and occasional linear groups. Examples of this province are Newer Volcanics of western Victoria and younger volcanics of northern Queensland. They are characterized by olivine basalt, extensive flows, small cones and a low explosion index. The Aereal Province is Pleistocene (the last 2 m.y, Ollier, 1978).

Cainozoic volcanism seems to occur on tensional zones in western Victoria and north Queensland. It is probable that volcanism only occurred in areas of tension and that such areas at any one time were restricted to a relatively narrow band parallel to the axis of the Eastern Highland.

The lack of youthful volcanism in eastern Australia is thought to be due to the crust of this area now being in compression, as indicated by reverse and wrench faults (Tectonic map of Australia and Papua New Guinea, 1971, on scale of 1:5,000,000).
II. MORPHOLOGICAL EXPRESSION OF VOLCANIC FEATURES (with particular reference to aerial photograph interpretation).

II. 1. Volcanic centres associated with plate tectonic movement and their recognition on the aerial photographs and Landsat imagery.

Volcanism is associated with three major structural environments. First on the area formed by compression which results in island arc and trenches. The second is volcanism in the tensional area where two plates move away from each other, eg. Mid-ocean ridges. These two structural environments are related; the motion of plates from a mid-ocean ridge to a trench provides the upper half of the convection loop (McKenzie & Richter, 1976). The third types are hot spots where rising jets of hot magma create chains of oceanic volcanoes, such as the Hawaiian Islands.

On active volcanoes the recognition of the volcanic centre is not difficult, because the morphological features (craters, caldera etc.) and the materials produced by its activities (flows, lahars etc.) are still visible. On the extinct volcanoes especially those older than Pleistocene, the morphological features are harder to recognise, because of the effects of erosion. The centres of such extinct volcanoes may be interpreted by identifying the volcanic infrastructure, such as ring dykes, radial dykes, volcanic plugs or caldera structures, maars and in extreme cases the facies changes between lava flows and clastic sediments.

On the aerial photographs, morphological expression of volcanic plugs,
Plate 1.

Landsat imagery covering the eastern part of Flores island Indonesia. All volcanoes in this area are extinct. The volcanic centres can be seen clearly using a magnifying glass. These islands are included in the volcanic arc in the Indonesian arc-trench system (Banda arc). The cloud cover is about 5%, but it concentrates over lands. The imagery was taken on 20th October 1973.
calderas, maars, ring dykes and lava flows can be recognised fairly easily. But for eroded volcanic centres, the Landsat imagery can still be used effectively, since it gives small scale over-view of the terrain (Plate 1) and concentric or radially centred structures stand out.

On plate 2, the volcanic centres can be grouped into four morphological units based on the shape of the volcanic cone, the existence of dykes and the topographic features (the morphological age).

1. The youngest morphological unit.

The whole elements of a volcano can be seen on this unit, eg. volcanic cone, caldera, crater, volcanic product (lava flow and pyroclastic materials where distribution can be traced radially from the vent), radial and dendritic drainage pattern, parasite cone and the junction of rock distributions between two volcanic vents. The dark grey, circular shape on the top of the volcanic cone is a crater lake that supports the identification of the youngest volcanic vent distinguishable.

2. Erosion activity has been working and reducing the volcanic cone height. Some cones do not have circular or elongate craters, but are dissected and form half cones. The craters are still recognisable and radial drainage pattern possibly associated with radial dykes give distinct landforms. On the submerged islands where the volcanic centre exists, the crater represented by the shape of the island can provide a good landform (No 2a on
Plate 2.
Landsat imagery of West Flores, Indonesia showing the morphological differences of volcanic centres. The volcanic evolution can be grouped with numbers, 1, 2, 3 and 4 based on the shape of cones, the existence of dykes and associated topographic features (see the text).
3. Morphological features No. 3, where deep erosion has been working, the volcanic centres can still be recognised by the remnant superstructure. Some conical erosion slopes (very gentle slope) associated with radial dykes are the main criteria of this morphology. Some parallel dykes associated with radial drainage and a gentle slope of cone formed a gentle topography where the lithological facies changes are marked by photographic tone changes. Crater No. 3a has a circular ring of light grey tone, where the lithological unit changes. Dark grey tone on the Landsat imagery indicates that the ground-water level in this unit is very high (Wilson, 1976), it also indicates that this unit might be formed by loose fragments and the ground water filling the space of intrafragments.

4. Morphological features No. 4, where the topography is nearly flat. The volcanic centre identification is very poor. Some dykes (it is usually parallel dykes) associated with circular lineaments and monoclinal hills can be used for interpreting the volcanic centres. In flat areas the occurrence plugs is indicative of volcanic infrastructure.

These volcanic centres can also be interpreted on aerial photographs, but in many cases mosaics must be constructed to cover the whole of each feature and then the scale reduced.

II. 2. Plateau basalts and their morphology.
<table>
<thead>
<tr>
<th>No.</th>
<th>Volcano Type</th>
<th>Morphology</th>
<th>Intensity of Explosion</th>
<th>Volcanic Materials</th>
<th>Macma Composition</th>
<th>Example Active/Inactive</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Hawaiian</td>
<td>Shield volcano</td>
<td>Low</td>
<td>Lava flow, gas, very small ash</td>
<td>Basalt</td>
<td>Mauna Loa active</td>
<td>1. Pele's hair</td>
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<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>2. Fountain of lava</td>
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<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>3. Ash, pahoehoe</td>
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<tr>
<td>2.</td>
<td>Strombolian</td>
<td>Strato-volcano</td>
<td>Moderate</td>
<td>Lava flow, gas, white cloud, ash (little).</td>
<td>Intermediate</td>
<td>Merapi (Java) active</td>
<td>1. Regularity of eruption</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>2. White cloud lava flow</td>
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<tr>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td>Cauliflower-shaped</td>
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<td>3.</td>
<td>Vulkanian</td>
<td>Strato-volcano + large caldera</td>
<td>Strong</td>
<td>Lava flow, gas, ash, broken fragments of crater plug, pyroclastic materials</td>
<td>Intermediate</td>
<td>Krakatau (Java) active</td>
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<td></td>
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<td></td>
<td>Glowing cloud</td>
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<tr>
<td>4.</td>
<td>Pelean</td>
<td>Strato-volcano + Plug done</td>
<td>Strong to extreme</td>
<td>Basic-ardente, pyroclastic materials, plug in crater, very small ash and lava flow</td>
<td>Viscous magma, intermediate</td>
<td>Mount Pelee active</td>
<td>Flat layered lava flow</td>
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<td>5.</td>
<td>Icelandic</td>
<td>Plateau Basalt</td>
<td>Low to moderate</td>
<td>Lava flow, gas, ash</td>
<td>Basalt</td>
<td>Laki (Iceland) active</td>
<td>Flat layered lava flow</td>
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<td>6.</td>
<td>Sulfataric Stage (sofet)</td>
<td>Plateau</td>
<td>Very low to moderate</td>
<td>Gases: SO₂ and CO₂</td>
<td></td>
<td>Bieng plateau (Java - extinct)</td>
<td>Yellowish cloud</td>
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<td>8.</td>
<td>Rift System</td>
<td>Scoria cone, ring dyke, graben</td>
<td>Low to moderate</td>
<td>Lava flows and pyroclastic</td>
<td>Basalt</td>
<td>Rift system in East Africa</td>
<td>Graben faults, subsidence area</td>
</tr>
</tbody>
</table>

Table 1 - Volcano classification
Fig. 11. DECCAN PLATEAU BASALTS INDIA.
Bullard's volcanic classification (1976) is based on Lacroix's concept, but he added two types of volcanic forms on the morphological features and volcanic cycles. The phreatic explosion characterized by specific landforms (Ollier, 1969) has also been added to Bullard's classification (Table 1).

Plateau basalts are formed where millions of cubic km of low viscosity basaltic magma is poured out through a fissure. It usually happens during the latest stage of orogenesis or in tensional rift systems in extensive, stable, flat areas. The lava flows remain as topographic plateaux. On the plateaux themselves can be found some subsidiary morphological features such as: plugs, domes, volcanic necks, craters, individual lava plateaux, conical hills, gorges and water falls over flow layers, lava domes, cuestas, volcanic depressions, linear ridges and fault-line valleys. Such features have been described on the Deccan plateau basalts (Rao, 1978). Plateau basalts in India (Fig. 11) have a regional slope between 0° to 4°, and they are characterised by lava plain morphology. Those lava plains are separated by a range of flat-topped hills.

In the Columbia Plateau basalts, U.S.A., some ring dykes which form craters and calderas have been investigated intensively, and it was found that the circular craters are formed from dome shaped hills; remnant ring dykes are exposed after erosion of the domes. These remnants of dykes erode out in crater or caldera-like forms and they can be seen on Landsat or Sky-lab imageries (Hodges, 1976). She suggested that the eruption in Odessa,
Fig. 12. Sequence of events postulated to explain the basaltic ring structures near Odessa. A = Roza flow ponded over a topographic low. B = Intersection of rising ground-water table with molten interior of flow, causing explosive venting through the crust as well as simple doming and cracking. C = Subsidence of the crust, with intrusion of lava into fractures concentric to focus of pressure release; surficial landforms composed largely of tephra. D = Present landscape after erosion of most of the fragmental material by the Missoula floods (After McKee, 1970).
U.S.A. area was accompanied by phreatic explosion of very shallow magma chambers (Fig. 12). McKea (1970) called these "sag flow out". The plateau basalts consist of individual lava flows which can be recognised in the field by macro and micro structures; these will be discussed below under lava flows.

II. 3. Shield volcanoes and their genesis.

The plateau basalts are built by basaltic, low viscosity magma. The magmas are poured out through long fissures on flat, vast areas. Eventually the eruption may become central, because part of the fissures are blocked by cooling magma. Blocking of fissures leading to the formation of shield volcanoes may form in this way, eg. Icelandic volcanoes. Elsewhere, shield volcanoes may form directly above hot spots (eg. Hawaiian volcanoes).

On the flank of shield volcanoes, some lava structures can be found. The minimum thickness requirement for individual flows which can form macro and micro structures is about 6 m (Waters, 1960). Typical examples of a shield volcano type are the Hawaiian volcanoes, which have been active since 1½ million years ago. Since this period the volcanic activity shows a variety of developmental forms.

Central eruption above hot spots or central eruption formed by blocked fissures show alignment of volcanoes (eg. Galapagos islands Fig. 13). From such volcanic alignments, major crustal fractures and their directions may
Fig. 13 — Volcano lineament and volcano spacing of the GALAPAGOS Islands.
be interpreted. It is probable that the mode of volcano spacing represents the thickness of the lithosphere below these volcanoes (Mohr & Wood, 1976).

II. 4. Strato-volcanoes or composite volcanoes.

Strato or composite volcanoes are volcanoes having a cone built by stratified pyroclastics. The strata consists of lava flows and pyroclastic materials bombs, lapillis, ash). Strato-volcanoes usually reach the maximum height, because firstly the lava flows protect the loose materials from erosion and secondly the long continued activity enables rapid build up and repair. The symmetrical cone shape indicates that the pyroclastics blow out through a central vent. The compositions of the strato-volcanoes are usually andesitic rocks.

The symmetrical steep-sided cone depends on tephra falling back around a small pipe-like (central vent) to give them their regular conical shape, but if this cone reaches large size and remain symmetrical, it must be strengthened by ribs of interbedded lava. Without them the loose cinder and ash are unstable and the cone tends to slump down.

Some volcanoes have been found where the tephra and ash materials falling back around the vent still have sufficiently high temperature to crystallise and form ignimbrite or welded tuff on the flank of the cone.

The stratified layers can be seen on the inner wall of the craters
PLATE 3.- Cuestas formed by lava flows in the nested caldera of the Batur volcano, Bali Indonesia. The vents growing from northeast to southwest and at least three stages of lava flows can be recognised. The darkest colour of lava flows is the most recent eruption of 1963.
which have been enlarged to a funnel shape either by explosion or internal landsliding. The proportion between lava flows (Bullard called "coulees") and the fragmental materials is approximately 1 to 370, that is why the coulees cannot be seen within stratified layers.

Some conduits are blocked by plug domes or plugs, so the new eruption will look for the weakened wall of the cone and form a parasite cone. In Batur volcano, the vents move southwest along the fracture zone (Plate 3).

The intensity of explosion of the strato-volcanoes is moderate to strong, so some eruptions destroyed the top of a composite volcano.

On the aerial photographs and Landsat imagery the strato-volcanoes have a good topographic expression. The symmetrical cone or asymmetrical cone standing on flat area or forming an island are easily recognised. The distribution of volcanic products resulting from each eruption can be separated and recognised by the different tones and morphology associated with each flow feature. On the photographs the newest lava flow gives a dark grey to black tones, but on Landsat and SLAR imageries the different tone domains are not always different in age. On the composite colour of Landsat imagery, the newest lava flow or lahars can be recognised as a dark grey tone associated with "finger landform" running from the vent for lava flow, and light grey to white tone and forming "braided stream" running from the vent for lahars.
Table 2. The differences between crater and calderas.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Crater</th>
<th>Caldera</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Shape and size</td>
<td>circular or elongate, symmetric or asymmetric. It is usually less than 1 km</td>
<td>it is always asymmetric, elongate depression topography. It is larger than 2 km.</td>
</tr>
<tr>
<td>2. Topographic features</td>
<td>the inner wall is steeper than outer wall. Some have crater lake.</td>
<td>the inner wall is always vertical, if not, it must be filled by talus or new intrusion. More than 80% have lakes inside.</td>
</tr>
<tr>
<td>3. Genesis</td>
<td>eruption processes, where the pyroclastic materials blow out from the magma chamber</td>
<td>tectonic processes, the emptied magma chamber wall falls down accompanied by intrusion or new vent.</td>
</tr>
<tr>
<td>4. Floor and the interior features</td>
<td>Plugs or dome plugs, spines, crater lake may occur.</td>
<td>craters, plugs, vast lakes flat floor associated with sand deposits.</td>
</tr>
<tr>
<td>5. Characteristic form</td>
<td>single, chain of craters and parasite crater.</td>
<td>multiple calderas associated with block faults.</td>
</tr>
</tbody>
</table>
II. 5. Craters, calderas, crater lakes and maars.

Pyroclastic materials thrown out through the conduits and falling back around the vent to form a concave circular crater. The differences between crater and caldera is mainly on size, genesis and morphology (Table 2).

Van Bemmelen (1949) illustrated the growth of calderas in Toba, Sumatra. He divided the genesis of the caldera into 5 steps. When the violent eruption blew out its top and left a large depression caused by collapse of the summit wall filling the emptied magma chamber, Topographically many calderas are marked by distinct fault lines bounding subsided blocks and the tops of fault blocks sometimes make topographic benches within the caldera rim.

Crater lakes are lakes formed by rain water filling the summit crater. The floor of the crater is impermeable and the water constitute an additional hazard on eruption. Crater lakes can be recognised on aerial photographs, because the water reflects the sun light and gives very bright photographic tone, but if the sun light is not reflected by the lake water the photographic tone is dark grey to black. On Landsat and SLAR imageries, the crater is always black in tone.

If ascending magmas above hot spots or subduction zone or in tension zones connect with ground water they will produce a violent explosion. Sometimes the explosion is followed by out pouring of lava, but many known
phreatic explosions do not have lava flows; they form topographic depressions or maars which have been reported from several areas in the world.

In Victoria (Southeast Australia), maars are formed by phreatic explosion within porous limestone (Ollier, 1967). This evidence can support the theory of phreatic explosion, but the feature in Eifel (Germany) where the name maar originated, is situated in a plateau of Devonian shale (an aquiclude layer) which would be unfavourable for phreatic explosion. The concept that phreatic explosion in the Columbia plateau (Hodges, 1970), can be explained by the genesis of basaltic ring structures near Odessa U.S.A. is illustrated in Fig. 12.

Maars can be distinguished easily under stereopairs by their crater wall which is steep inside and gently sloping outside (3° to 4°), their circular shape, and by the fact that the maar floor is below the average topographic level of its surroundings. Some maars are filled by rain water or rivers to form a lake. Maars do not have any apparent outlet for the water.

The flat floor of the drained and swampy maars indicate considerable infilling of the original crater, but the materials filling the crater and how they filled it are not yet known. Some geologists suggest that the volcanic materials blown out, fall back to fill the new crater. The gravity forces adjust the infilling materials to be flat (Ollier, 1969).

Maars erupt materials of basaltic rock composition (Rittmann, 1962).
Fig. 14a. Ponded basaltic lava flow on old topographic relief.

Fig. 14b. Structures of flow tops on basaltic lava. (After Waters, 1960.)
reported maars in acid magma, but Ollier (1967) suggested that maars are generally formed by basic magma, because acid and intermediate magmas will give rise more often to simple cones or calderas.


In the discussion of shield volcanoes, it was mentioned that the minimum thickness of lava flow which can form internal structures is about 6 m. Olivine basaltic lava flows show the fewest internal structures, because they are very liquid and can flow for long distances. The flow structures depend on the slope angle of the volcanic cone, the lava compositions, the topographic surface on which the flow occurs, and also the amount of included fragmental materials (xenoliths) in the lava. Basaltic lava (tholeiitic basalt) flows may show the following features (Columbia plateaux):

a. Structures of flow tops.

On the individual lava flow the structures of flow can be recognised as aa lava, pahoehoe lava surface. On the aa lava type, the flow tops structures can be recognised as deep as 4.5 m (Fig. 14). Structures of flow tops cannot be used for detecting the direction of lava motion. In places a general idea of the flow direction may be gained by study of the orientation of the steep slabs that inject the cinders tops from below. The long dimension of the slabs are consistently about at right angles to the direction of flow and the steeply imbricated slabs generally dip toward the source of lava.
Fig. 15. - Columnar jointing growth in basaltic lava flow under static condition (A) and with renewal movement after partial solidification (B) (Waters, 1960)
On pahoehoe lava, the surface shows abundant minor features such as ropes and cords, lobate ridges, stretched vesicules, pulled glass filament, broken and distorted bubbles, skid marks, lava flutings, pressure ridges and pressure cracks, schollen-domes. Ropy folds of lava may extend either parallel or at right angles to the direction of motion.

Surface features soon disappear by weathering and in superposed flows, they are generally concealed under blocks that have slid down from the flow above.

b. Structures of flow interiors.

1. Inclined columns in flow centres.

Columns grow at right angles to isothermal surfaces within the cooling lava, but if the lava is thin or if cooling is rapid and irregular, columns may not form, instead, the lava flow breaks into hackly fragments or joints irregularly (moraine lava structures). The columnar jointing can be divided into two types depending on their genesis. First a lower tier of coarse but generally well shaped columns, grows upward from the base of each slab and secondly longer tiers of thin and more irregular columns spouts downward from beneath the flow tops. The two tiers meet along a prominent horizontal parting about two third of the distance from the top of the flow (Fig. 15). Under normal conditions of static crystallization (Fig 15A), isothermal surfaces are nearly horizontal and so the tiers stand vertical. But if forward movement of lava is resumed after columnar jointing have grown in some distance from the top and bottom of
Explanation Figs. 16 and 17.

These micro and macro structures can be used to determine the lava flows source or vent and to prove the photo-interpretation which is based on the top flow structures.
Fig. 16. Bottom structure of basaltic lava flow in the Columbia River basalt. A = Large spiracle with lobate walls from a thick mass of aa clinker; B = Spiracle with tongue-like clusters of vesicles rising from a pit in the underlying pahoehoe flows top. (After Waters, 1960).

Fig. 17. Bottom structure of basaltic lava flow in the Columbia River basalt. Pipe vesicles (a) and vesicle cylinders (b). (After Waters, 1960).
flows, the isothermal surfaces will be tilted, because of transport of hotter lava near the vent over the already solidified lava tier columns (Fig. 15B). So using this structure, geologists can determine the direction of lava motion.

On aerial photographs, where the lava is exposed, (eg. Giant's Causeway, Co Antrim, Northern Ireland), the polygonal cooling joint structure is apparent. Smaller examples of this structure are common.

2. Filled lava tubes.

Many of the olivine basalts contain in numerous filled lava tubes. The trend of the lava tubes and their internal jointing afford reliable evidence of the direction of lava flow.

Lava tubes can be formed by lava pouring down the steep slopes and gradually crusting over, before they disappear into the flows which they feed. Other tubes are formed by protrusion of finger like extrusions and broader tongue-like flow units from the front of advancing flows.

In the filled lava tubes columnar joints grow inward from the roof and walls of the tubes, giving a radial structure that resembles the feathers on an Indian headdress.

c. Structures preserved near fronts of laterally spreading flows.

Near the front of thick lava flows a series of prominent vertical
fractures which trend roughly parallel with the direction of lava motion, may be found. These structures are formed by tension cracks, similar in orientation to the longitudinal crevasses that develop in the front of glaciers. The tension cracks in lava are easily distinguished from post solidification tectonic faults and fractures, because they are restricted to the upper part of the lava flow, they do not cut the lower tiers of columnar joints. These fractures are useful in determining the direction of the source of lava flow, but they are hard to find in the field.

d. Structures of flow bottoms.

On the flow bottoms of basaltic lava flows can be found structures as follows:

Spiracles (Fig 16) and pipe vesicules (Fig. 17).

Water vapour and other gases surge upward into liquid lava are produced on a lava flow covering marshy ground. Trapped pockets of air, gases from burning vegetation, and steam expelled from soils and water soaked sediment may also boil upward into a flow. These vapours chill the lava, freezing it to basalt glass along the margins of the jets of escaping gas. If the chilling is rapid, the gas channels may be preserved intact when the flow congeals. The upper ends of most gas chimneys and tubules bend in the direction of lava motion. The large gas chimneys are called spiracles with diameter from few cm to scores of tens cm. They are nearly circular in cross section, but as they bend forward in the direction of lava flow, they flatten, even acquire a linear fluting and break up into strings of vesicles. In the Columbia River basalt U.S.A., some or nearly all spiracles are more than
3 m in diameter, and they are partly filled with pillow lava and palagonitized glass breccia, so that pillow lavas can be found within massive lava flows.

Other features of flow bottoms such as distorted and overfolded clays and soils that have been overridden by nearly solid lava, tree molds found in the base of lava flows (clusters of vesicles and streaks of whitish alteration caused by gases released from the wood, strung out from the tree in the direction of flow) are not discussed.

II. 7. Dykes and eroded volcanic centres.

On theory the rising magma column will form a high magmatic pressure. This energy will form a dome structure. On the dome structure may be found radial, ring fractures, where the magma was injected as dykes, volcanic diatremes and stocks (Holmes, 1970). On deeply eroded volcanic centres, such as at Warrumbungle, Gilgandra N.S.W. and Gilberton, Queensland, Australia, the radial and ring dykes can be seen clearly on the aerial photograph.

The ring dykes in the Gilberton area the photo-interpretation can add the intrusion, while the ring dykes differentiation cannot be recognised (Fig. 19 a.b, Plate 5).

In tropical areas where the chemical weathering process works intensively, the dykes are hard to recognise under stereoscope, except
they form a positive topography. Some dykes in the tropical areas form a negative topography, they can be recognised on aerial photograph by their structures (such as dome and anti dome structure, circular features). In arid regions dykes usually form a positive topographic feature (Plate 4) and they usually are aligned.

The composition of dyke is usually the same as the lava flow formed by the same vent. The differences might be expected on textures and structures of the minerals.

Dyke swarm formed by volcanic depression usually have a good pattern (parallel, radial and ring dykes). The different composition of these dykes might depend on the time where the fractionation and contamination affect the late magma composition.

II. 8. Example of photo-interpretation.

Two examples of volcanic features were examined to construct the effects of erosion depth. The eastern part of the Warrumbungle province provides an example where erosion has removed the volcanic superstructure and revealed feeder plugs. The Paleozoic Bagstowe complex near Gilberton Queensland, illustrates the effects of deeper erosion to a ring dyke stage.

a. Gilgandra sheet.

Plugs intruding the Garrawilla volcanics in an area east of Coona-
barabran are covered by an excellent cloud-free stereopair. The area is mostly grazing land with light forest covers.

The dominant rocks in the area are the Mesozoic Pilliga Sandstones and Garrawilla Volcanics; both are intruded by alkaline plugs which form positive topographic features (Fig. 18b).

Permian sediments are shown on the geological map Fig. 18a flanking the plugs. Aerial photo study indicates that this unit is more extensive and may in part consist of older intrusives. The plugs are easily recognised by the dark tone due to less intense reflection and heavier timber cover. They have radial drainage and concentric dip ridges about them. The plugs can be distinguished from volcanic cones by the lack of craters.

Small radiating dykes are shown on the geological map; they are too small to be identified on the aerial photos. A possible dyke was identified to the east, see photo plate 4.

Several faults not shown on the geological map were recognised. A synclinal structure to the northwest of the plugs may be part of a rim syncline.

b. Bagstowe ring dyke complex in the Gilberton area.

A good quality of aerial photographs of the Bagstowe complex were examined. The boomerang-shaped ring dykes forms a narrow ridge and is
Fig. 18a. A part of the geological map of Gilgandra N.S.W. Australia on scale of 1:250,000.
Fig. 18b. Photogeologic interpretation of the Gilgandra, NSW Australia. Scale appr. 1:84,000, taken on 17 DEC. 1967. Qa = alluvium; 2 = Garrawilla Volcanics; 3 = intrusion; 4 = older intrusion; 5 = syncline; 6 = fault; 7 = photographic centre point; 8 = dip slope 5 to 10°; 9 = dip between 10° to 20°.
clearly seen without stereoscope, because of the tone difference between the trachytic dyke and granite country rock. In spite of its clear expression the dyke has little effect on the drainage pattern, except that small tributaries are locally perpendicular to the dyke.

The granite (Dg) has medium, dendritic drainage pattern and grey tone. At point C the photographic tone is very light grey, possibly because of soil erosion and thin grass cover. Some parallel dykes in this unit can be recognised on point D. Smaller intrusions of Cg (?) can be seen on the western part of the boomerang ridge.

The edge of an adjacent ring dyke complex can be recognised on the eastern side of the area, but the different lithological units cannot be separated (Point A). Smaller intrusions (Cg) related to this centre occur at the northern end of the ring dyke. The drainage pattern of Cg is not clear, but the tone is darker and the texture is finer than the granite (Dg). The contact area between those units creates abundant lineaments which parallel the intrusion and make "braided stream like" texture (Point B).

Some photographic lineaments indicated by photographic tone, ridges and straight river segments were recognised. Some were interpreted as marking faults (Point E), quartz veins (Point G) and parallel dykes (Point D and F).

The big faults which have trend NNW offset the boomerang ring dyke on point E, and some intrusions which follow the fault pattern were reco-
Fig. 19a. Geological map of GILBERTON, Queensland Australia, showing the location of the Bagstowe ring dyke. (Redrawn from Plate 38 in Volcanic Cauldrons, Ring Complexes and Associated Granites of the Georgetown Inlier Qld. by Branch C.D. 1966.) 1:500,000.
Fig. 19b. Photo-interpretation of the Bagstowe ring dyke. Legends are the same as ones on geological map.
CAINozoic

- Qa: Alluvium
- Czc: Basalt

MESOZOIC

- K: Conglomerate, sandstone.
- Pzu: Mainly porphyritic rhyodacite.
- Pa: Andesite, rhyodacite welded tuff.

PALEOZOIC

- Cd: Pink leucocratic adamellite.
- Cg: Trachyandesite to adamellite.
- Cd: Pink adamellite with rhyodacite margin.
- Cb: Mainly rhyodacite welded tuff with some viscous flows and pyroclastics.
- Dg: Devonian granite intruding Georgetown Inlier.

PRECAMBRIAN

- Pe: Metamorphics and granite in the Georgetown Inlier.

--- Fault

- -. Acid igneous dyke

--- Photo lineament

\( \text{Dip slope / triangular facet} \)

\( \text{Dip between 30° - 45°} \)

\( \text{Dip} > 45° \)

Fig. 19c. Legend figures 19a and 19b.
recognised on point F. Both features are not recorded on the published geological map of Gilberton Queensland on scale of 1:250,000 and 1:500,000.

The Precambrian metamorphics (Pe) have very fine texture, dendritic pattern and abundance of photo-lineaments. The boundary between the Precambrian rocks and the granite (Dg) forms a distinctive curving photographic lineament (Point G). It forms a low, curved ridge with white strips (Quartz vein dykes (?)). The curving boundary was followed by the Cg intrusion shape, it indicates that the Cg dyke intruded following the curve fractures resulted from the cooling process of the granite Dg. The photo-interpretation of this boundary is larger on the northern part and on the southwest of the plate 5.
III. PHOTOGEOLOGICAL INTERPRETATION OF THE WESTERN PART OF VANUA LEvu, FIJI.

1. INTRODUCTION.

1a. Remote sensing and geological mapping.

Remote sensing is one of the modern methods to detect the nature and structure of the Earth's surface features, recently added to geological mapping. It refers to the acquisition of data about target objects by instruments or sensors not in contact with them.

In certain areas, where the Landsat imagery or aerial photography is available, regional geological mapping can be done quickly at low cost. The accuracy of geological information depends on the availability of finance, time and the geologist's ability. Remote sensing methods can further reduce the expense of obtaining the same quality of geological data by field reconnaissance geological mapping.

Air photography is fundamental to the preparation of almost all such maps. Air photographs are not only used to make the basic maps, but also vital to the field geologists as a source of geological information and as a compilation base and for navigation.

Regional geological mapping can be done by Landsat on a scale of 1:250,000 or aerial photographs on a smaller scale, while detailed geological
Fig. 21. Photo-index map of 1:40,000 scale aerial photographs.
Table 3: List of aerial photo on scale 1:40,000 covering Vanua Levu (taken on June 1954).

<table>
<thead>
<tr>
<th>No</th>
<th>Run No.</th>
<th>photo No.</th>
<th>Quantity</th>
<th>Quality</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>1</td>
<td>001 - 039</td>
<td>39</td>
<td>good</td>
<td>Yangganga island</td>
</tr>
<tr>
<td>2.</td>
<td>2</td>
<td>039 - 082</td>
<td>44</td>
<td>good</td>
<td>North coast</td>
</tr>
<tr>
<td>3.</td>
<td>3A</td>
<td>140 - 147</td>
<td>8</td>
<td>good</td>
<td>North coast M.F.</td>
</tr>
<tr>
<td>4.</td>
<td>3B</td>
<td>056 - 066</td>
<td>11</td>
<td>good</td>
<td>Naselesele</td>
</tr>
<tr>
<td>5.</td>
<td>3C</td>
<td>001 - 017</td>
<td>17</td>
<td>good</td>
<td>Ndreketi</td>
</tr>
<tr>
<td>6.</td>
<td>3D</td>
<td>052 - 077</td>
<td>26</td>
<td>fair,50% cloud</td>
<td>Lambasa–Undu</td>
</tr>
<tr>
<td>7.</td>
<td>10A</td>
<td>131 - 138</td>
<td>8</td>
<td>good</td>
<td>Monkey Face</td>
</tr>
<tr>
<td>8.</td>
<td>4A</td>
<td>005 - 041</td>
<td>37</td>
<td>good</td>
<td>Nasarowangga</td>
</tr>
<tr>
<td>9.</td>
<td>4B</td>
<td>079 - 100</td>
<td>22</td>
<td>90% cloud</td>
<td>Undu</td>
</tr>
<tr>
<td>10.</td>
<td>5A</td>
<td>102 - 137</td>
<td>36</td>
<td>good</td>
<td>Mbuia</td>
</tr>
<tr>
<td>11.</td>
<td>5B</td>
<td>001 - 019</td>
<td>19</td>
<td>cloudy</td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td>6A</td>
<td>092 - 101</td>
<td>10</td>
<td>good</td>
<td>Ndama</td>
</tr>
<tr>
<td>13.</td>
<td>6B</td>
<td>116 - 130</td>
<td>15</td>
<td>good/fair</td>
<td>Vutusinga</td>
</tr>
<tr>
<td>14.</td>
<td>6C</td>
<td>052 - 082</td>
<td>32</td>
<td>30% cloud</td>
<td>Central ridge</td>
</tr>
<tr>
<td>15.</td>
<td>7A</td>
<td>001 - 011</td>
<td>11</td>
<td>high tilt &amp; tip</td>
<td>Ndriti gap</td>
</tr>
<tr>
<td>16.</td>
<td>7B</td>
<td>028 - 041</td>
<td>none</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.</td>
<td>7C</td>
<td>020 - 029</td>
<td>10</td>
<td>good</td>
<td>Nambua</td>
</tr>
<tr>
<td>18.</td>
<td>8</td>
<td>033 - 059</td>
<td>27</td>
<td>good/fair</td>
<td>Nambouwolu</td>
</tr>
<tr>
<td>19.</td>
<td>9</td>
<td>058 - 082</td>
<td>25</td>
<td>good/fair</td>
<td>Nasalo - Savusavu</td>
</tr>
<tr>
<td>20.</td>
<td>10</td>
<td>105 - 111</td>
<td>7</td>
<td>good</td>
<td>South coast</td>
</tr>
<tr>
<td>21.</td>
<td>10B</td>
<td>096 - 104</td>
<td>7</td>
<td>good</td>
<td>South coast</td>
</tr>
<tr>
<td>22.</td>
<td>11</td>
<td>018 - ?</td>
<td>none</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*These aerial photos are available at the Mineral Resources Department, Suva Fiji.
maps can be made using larger scale aerial photographs and SLAR imageries supplemented by field work. Colour aerial photographs are more useful, because they give a lot of informations in natural colours about the Earth's surface.

1b. Preparation for study area.

1b.1. Aerial photographs and Landsat imageries covering Fiji area.

Vanua Levu island is covered by four types of aerial photographs. The first type is at a scale of 1:40,000, flown in June 1954, it does not cover all the island (Fig. 21 and Table 3). The photograph quality is good, except for the ones covering the eastern part of Vanua Levu, where the cloud cover is more than 70%. The second type of aerial photograph was taken on August 1967, on a scale of 1:24,000. These aerial photographs were taken over selected areas for mineral exploration purposes. Their quality is good, with cloud cover between 10 to 20%. The third type are aerial photographs of a good quality taken on August 1973 by RAF on a scale of 1:80,000 (Fig. 22, Table 4), (except at Undu point where cloud covers range between 80 to 90%). The fourth type are aerial photographs on a scale of 1:20,000, taken in 1976, for road making purposes, their quality is very good, without cloud cover. Aerial photograph type 1, 2 and 3 are available at the Mineral Resources Department, Suva, Fiji, while aerial photo type 4 is available at the Lands Department of Fiji in Suva.

Landsat imagery covering Fiji islands is also available at the
Fig. 22. — Photo-index map of 1:80,000 aerial photographs.
### Table 4: List of aerial photo on scale 1:80,000, taken on 16th July 1973.

<table>
<thead>
<tr>
<th>No</th>
<th>Run No</th>
<th>photo No.</th>
<th>Quantity</th>
<th>Quality</th>
<th>Remark/location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>1</td>
<td>001 - 018</td>
<td>18</td>
<td>good</td>
<td>no cloud, dark printing, Northern of Undu point.</td>
</tr>
<tr>
<td>2.</td>
<td>2</td>
<td>026 - 043</td>
<td>18</td>
<td>good</td>
<td>cloud cover &lt; 10%, dark printing Lambasa - Undu</td>
</tr>
<tr>
<td>3.</td>
<td>3</td>
<td>054 - 079</td>
<td>26</td>
<td>good</td>
<td>no cloud, Monkey Face - Lambasa</td>
</tr>
<tr>
<td>4.</td>
<td>4</td>
<td>008 - 044</td>
<td>37</td>
<td>good</td>
<td>cloud ± 10%, dark printing, Seseleka to Nambua</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>017 - 018</td>
<td>2</td>
<td>good</td>
<td>Nambua coastal plane, cloud &lt; 5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>022 - 026</td>
<td>4</td>
<td>good</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>023 - 057</td>
<td>35</td>
<td>good</td>
<td>cloud cover &lt; 1%, Ndriti - Savusavu</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>042 - 053</td>
<td>12</td>
<td>fair/good</td>
<td>very dark printing, cloud cover &lt; 5%, Natewa Bay</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>022 - 025</td>
<td>4</td>
<td>good</td>
<td>dark printing, Nambouwolu - Nasalo</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>0122 - 0130</td>
<td>9</td>
<td>good</td>
<td>Nasalo - Uluiyandali, dark printing</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>0046 - 0066</td>
<td>21</td>
<td>good</td>
<td>Eastern part is obscured by thin cloud, Savusavu - Rambi island.</td>
</tr>
</tbody>
</table>

* All aerial photos are held by Mineral Resources Department, Suva Fiji, but the negatives are in the U.K.*
Landsat is available in 2 bands (band 5 and 7).

Landsat is available in single band (see Table V).

Fig 23. Landsat index map of the Fijian islands.
<table>
<thead>
<tr>
<th>No.</th>
<th>Location/ band no</th>
<th>Scene number</th>
<th>Quality</th>
<th>Cloud cover</th>
<th>Scene centre point</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Path 67, Row 72</td>
<td>81192127500</td>
<td>Fair</td>
<td>60 %</td>
<td>S 17°15'50&quot; E 170°51'34&quot;</td>
<td>Cloud covering all small islands and Viti Levu more than 70 %.</td>
</tr>
<tr>
<td>2.</td>
<td>Path 82, Row 73</td>
<td>81432143500</td>
<td>Very poor</td>
<td>60 %</td>
<td>S 18°14'57&quot; E 175°09'55&quot;</td>
<td>No islands are free from cloud cover.</td>
</tr>
<tr>
<td>3.</td>
<td>Path 73, Row 73</td>
<td>81192113500</td>
<td>Fair</td>
<td>40 %</td>
<td>S 17°51'07&quot; E 170°03'30&quot;</td>
<td>Thin cloud cover obscures the land which is only 20 % of total imagery.</td>
</tr>
<tr>
<td>4.</td>
<td>Path 73, Row 72</td>
<td>81192135500</td>
<td>Poor</td>
<td>60 %</td>
<td>S 17°46'53&quot; E 170°29'05&quot;</td>
<td>Yasua Levu is covered by thin cloud, Viti Levu is covered by thick cloud.</td>
</tr>
<tr>
<td>5.</td>
<td>Path 73, Row 73</td>
<td>814132136500</td>
<td>Very poor</td>
<td>80 %</td>
<td>S 16°44'43&quot; E 170°03'11&quot;</td>
<td>Cloud cover on all the imagery.</td>
</tr>
<tr>
<td>6.</td>
<td>Path 73, Row 71</td>
<td>811921392500</td>
<td>Band 5 poor</td>
<td>50 %</td>
<td>W 179°48'12&quot;</td>
<td>Band 5 is very poor, while band 7 cloud covers all land which is only 20% of total imagery.</td>
</tr>
<tr>
<td>7.</td>
<td>Path 73, Row 72</td>
<td>811921394500</td>
<td>Band 7 fair</td>
<td>70 %</td>
<td>W 179°50'15&quot;</td>
<td>Band 5 is very poor, while band 7 cloud covers all land which is only 20% of total imagery.</td>
</tr>
<tr>
<td>9.</td>
<td>Path 73, Row 73</td>
<td>81192131502</td>
<td>Fair</td>
<td>40 %</td>
<td>W 179°28'35&quot;</td>
<td>Koro island is free from cloud cover, some volcanic centres can be recognised on Yasua Levu and Taveuni islands.</td>
</tr>
<tr>
<td>10.</td>
<td>Path 73, Row 74</td>
<td>81392113150</td>
<td>Poor</td>
<td>10 %</td>
<td>W 179°30'53&quot;</td>
<td>Totong and Niu are volcanic centre islands, are free from cloud cover.</td>
</tr>
<tr>
<td>11.</td>
<td>Path 73, Row 73</td>
<td>81392113150</td>
<td>Fair</td>
<td>20 %</td>
<td>W 179°30'12&quot;</td>
<td>Cloud covers the island, except Totong Isl.</td>
</tr>
</tbody>
</table>
Eros Data Centre, Department of the Interior, U.S.A., but the quality is very poor (Fig. 23, Table 5). The Landsat imageries are printed on a scale of 1:1,000,000, black and white and are taken at various times through the year, unfortunately the cloud cover is very high. Thus, the Landsat imageries do not help much on photo-interpretation of this area.

1b.2. Base map.

A base map on a scale of 1:100,000 was used for plotting the photo annotation. This was reduced from a topographic map at a scale of 1:50,000. The reduction was made with the Kail double mirror projector. The contour lines of the base map are not drawn to avoid making complications.

The new road and all the transportation facilities were added to the base map, but the river names are not shown, except where needed for plotting purposes.

Conventional air photo-interpretation method was used in this project since the poor Landsat imageries could supply little data (Table 5).

1c. Previous work.

The first mapping on a scale of 1:50,000, was by Bartholomew in 1959. He worked to the west of Savusavu Bay (sheet 11, Fig. 24). Then followed Rickard (1970) who mapped Ndrua-Ndrua and Undu Point (sheet 1 and 2). Before the latter maps were printed; a reconnaissance map on a scale of 1:200,000 was published (Rickard, 1966). On this map, volcanic
Fig. 24 - Sheet index map of Vava'u Levu. Photogeological interpretation covers sheets no. 3, 4, 9 and 10.
stratigraphic divisions were erected, e.g. young volcanoes (Mbua and Taveuni volcanoes), middle aged volcanoes (Nararo Group) and older volcanoes (Natewa and Monkey Face Groups). The division is based on the morphological features and the relationship to intercone deposits of neritic facies. In a few places coral reef was found. The divisions are (Fig. 28): Mbua Group consisting of basalts, Nararo Group consisting of hornblende andesite, Undu Group which mainly consists of dacitic volcanics, and Natewa Group formed by sedimentary rocks mixed up with basic andesite breccias and flows.

Ibbotson (1969) mapped sheets No 6, 7, and 8; followed by Coulson (1970) who mapped sheets No 3 and 9 (Mbua and Monkey Face area) and Hindle (1976) who mapped sheets No 4, 5 and 10. The remaining sheets (No 12, 13 and 14) are in press.

Although all 50,000 sheets have been completed the mapping was carried out on a regional traverse basis with ca 2 km spacing generally; thus detailed photo interpretation coupled with ground checks can yield useful information and improvements on the geological maps.

2. REGIONAL STRUCTURAL SETTING OF FIJI.

The islands were probably formed by submarine volcanoes eventually growing into sub-aerial volcanoes; clusters of volcanoes of different ages make up the bigger islands.
Fig. 25. — Sea-floor spreading interpretation between New Hebrides Trench and Tonga Trench (After Chase, 1972, and Carney et al., 1978).
Chase (1972) suggested that some sea-floor spreading might occur within the Fijian area and a fossil sea-floor spreading ridge has been found between the Lau and Tonga ridges (Peggy Ridge) and also possibly between Viti Levu and the New Hebrides, and between Vanua Levu and the Solomon islands (Fig. 25 and 26).

Geophysical studies on the Fiji Plateau, Lau basin, South Fiji Basin and New Hebrides island arc (Green and Cullen, 1973; Hawkins, 1976; Carney, 1978) allows the following interpretation of the geological history:

a. First stage of volcano building, between 25 to 13 my.
   
   BP (Upper Oligocene – Middle Miocene).

The Pacific plate was subducted below the Indo-Australian plate. The west and southwest dipping subducted zone (Fig. 26) formed a double arc. The front arcs are Tonga and Vitiaz arcs. The rear arcs are Lau Ridge and the old New Hebrides islands (Maewo, Malekula and Pentecost islands.

Two main fractures have been found to be active since that period and one of them is still active today, it is called the Hunter Fracture Zone. This period ends with orogenic activity and intrusion of granitoids in Viti Levu.

b. Second stage between 13 to 5 my BP (Middle Miocene to Upper Miocene).
Fig. 26. The main structural element of North Fiji Plateau (After Chase, 1971; Hawkins, 1976 and Carney et al, 1978.)
The fracture zones developed as transcurrent faults. The northern transcurrent fault movement is faster than the southern one and activity ceased in the Vitiaz trench, while the New Hebrides trench developed. Recent interpretation suggests that the Vitiaz Trench is a relic continuation of the Tonga Trench (Gill, 1970). The sea-floor spreading between Lau Ridge and Tonga Ridge developed, and spreading developed in the Fiji Plateau (Fig. 25). Viti Levu and Vanua Levu islands began to rotate anticlockwise as much as 25° during continuous volcanism in Vanua Levu, consisting of basic andesites of the Natewa Group, and ending with hornblende andesite of the Nararo Group.

c. Third stage between 5 to 2 my. BP.

The sea-floor spreading accelerated well and a transcurrent fault resulted in a big offset between Tonga Trench and Vitiaz Trench, which is still active today. The sea-floor spreading ceased at the end of this period.

The New Hebrides Trench began to subduct to eastward, to form Pliocene volcanoes in these islands.

d. Fourth stage between 2 my, and present.

The youngest volcanic activity in Vanua Levu produced Mbua volcano (Taveuni island) Mbua basalt is dated between 2.9 to 3.3 my. (Table 6). The Mbua eruption might have followed older N-S fissures with the oldest
Legend Fig. 27.

PNG - Papua New Guinea.
NC - New Caledonia.
NZ - New Zealand.

1. - Australian plate above sea level (Antarctica is similarly hachured).
2. - Australian plate below sea level.
3. - Main chains of the Inner Melanesian Arc.
4. - Related areas of the Inner Melanesian arc.
5. - Outer Melanesian Arc and related areas.
6. - Indian/Antarctic-Pacific/Antarctic Ridge.
7. - Sialic Fijian mass.
8. - Subduction direction along Benioff planes.
9. - Megashears/tectonic faults systems.
10. - Seas, basins and Pacific plate.
11. - Sea-floor spreading and drift direction.
12. - Fault zone.
13. - Anticlinal axis.
14. - Basinal scarped edge.
15. - Trenches in black.
Fig. 27. The position of Fiji Plateau associated with the Island arc systems of the SW Pacific region. (After Avis, J., 1973; Green & Cullen, 1973).
eruption in the northern part. Taveuni volcanoes have a NNE trend and over 100 volcanoes were most likely erupted at the same time along a single fissure (Rickard, 1966).

The different lithologies of Vanua Levu create 5 morphological units (Fig. 28). The youngest basalts make up Mbua shield volcano and the Taveuni ridge. The drainage pattern on these basalt units is parallel and radial. Mbua caldera is formed by a cauldron collapse and some dykes filled the resulting fractures.

Second lithology is the Monkey Face Volcanic Group which is formed by basic andesite to basaltic breccias with monomict fragments, pillow lavas, flows and sedimentary rocks. These lithologies form undulating rounded morphological features. The volcanic breccias form more irregular ridges and some hill tops have good outcrop. Dolerite intrusions have been mapped by Coulson (1971), but in the field their morphology is not distinguished.

The third lithology unit is the Natewa Volcanic Group which has the largest distribution in Vanua Levu. It predominantly consists of volcanic rocks ranging in composition from basic andesite to basalt (Rickard, 1966). This unit forms moderate undulating morphological features in which the younger intrusions of Nararo Andesite from volcanic plugs.

The fourth lithological unit is Nararo Volcanic Group which is
Fig. 28.- Lithological distribution map of Vanua Levu (After Rickard, 1966.).
Table: 6. STRATIGRAPHY OF VANUA LEVU

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>EPOCH</th>
<th>Indonesian Letter classification</th>
<th>TIME (in million years)</th>
<th>Stratigraphic unit (Rickard, 1966; Hinde, 1976)</th>
<th>Volcanism Episode</th>
<th>Type of Volcanism</th>
<th>Volcanic production</th>
</tr>
</thead>
<tbody>
<tr>
<td>TERTIARY</td>
<td>Eocene</td>
<td>Upper Late h</td>
<td>3.5</td>
<td>2.9 - 3.3</td>
<td>Mbuav Volcanic Group</td>
<td>YOUNG</td>
<td>Sub-aerial Volcano</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower Early g</td>
<td>5.5</td>
<td>2.37 - 4.3</td>
<td>Nararo Volcanic Group</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.40 - 6.7</td>
<td>Natewa Volcanic Group</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Upper Late f3</td>
<td>9.0</td>
<td>4.18</td>
<td>Monkey Face Vol. Group</td>
<td>OLD</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Middle f1 - 2</td>
<td>12.5</td>
<td>3.7</td>
<td>Undu Volcanic Group</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower Early e</td>
<td>15.0</td>
<td>3.3</td>
<td>?</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>22.5</td>
<td>2.9</td>
<td>?</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
represented by hornblende andesite, plugs and small aprons of pyroclastics and reworked breccias.

3. PHOTOLUMINOLOGICAL UNIT DESCRIPTION.

3a. Preparation.

Lithological units on the air photographs were studied carefully and the distribution of each lithology was traced under the stereoscope. The characteristics of each lithological unit were based on tone, drainage pattern, morphological features, topographic level, vegetation cover, texture, structure, and the position of each unit with respect to major volcanic centres. The boundary between two units is drawn at the different morphological features, drainage pattern, tone and lineament, etc. Then photo-lithological units were compared with published geological maps, (see maps 1 and 2 back pocket).

Deposits of different volcanic centres have different characteristics depending on their composition and age. Volcanic cones are not formed by a single eruption or flow, but are formed by many eruptions at different times. When the cone was built, the erosion and deposition were active intermittently with flow. Periodic eruption producing different volcanic materials of andesitic composition together with small intrusions within the pyroclastics, will form a strato-volcano. In the basaltic shield volcanoes the flows reach long distances from the vent on smaller slopes.
<table>
<thead>
<tr>
<th>PHOTO-LITHOLOGICAL UNITS</th>
<th>MORPHOLOGY STAGE</th>
<th>DRAINAGE PATTERN</th>
<th>CHARACTERISTIC FEATURES</th>
<th>ROCK FORMING UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALUVIUM</td>
<td>flat, swampy</td>
<td>-</td>
<td>dark-grey tone</td>
<td>sand, mud and gravels</td>
</tr>
<tr>
<td>CONGLOMERATE</td>
<td>mature</td>
<td>dendritic</td>
<td>grey tone, grass cover</td>
<td>polymict fragment of basalt, sandstone and argellite</td>
</tr>
<tr>
<td>N'DRITI BASALT</td>
<td>mature</td>
<td>dendritic, angular</td>
<td>fine drainage texture surrounded by rough textures, some intrusions and faults</td>
<td>lava flows, and igneous intrusions</td>
</tr>
<tr>
<td>MBUGU BASALT 1</td>
<td>immature</td>
<td>rough, nearly radial</td>
<td>sharp ridges, coarse drainage pattern</td>
<td>lava flows and breccias</td>
</tr>
<tr>
<td>MBUGU BASALT 2</td>
<td>gentle slope, immature</td>
<td>medium to rough dendritic</td>
<td>V shaped valleys</td>
<td>lava flows and breccias</td>
</tr>
<tr>
<td>MBUGU BASALT 3</td>
<td>medium</td>
<td>dendritic</td>
<td>smooth texture drainage pattern</td>
<td>lava and breccias</td>
</tr>
<tr>
<td>MBUGU BASALT 4</td>
<td>medium</td>
<td>dendritic</td>
<td>sparse vegetation, grey tone and flows structures</td>
<td>lava and breccias</td>
</tr>
<tr>
<td>MBUGU BASALT 5</td>
<td>mature</td>
<td>medium texture</td>
<td>distinguishable from T92 by lava tongues and dense trees cover</td>
<td>lava and breccias</td>
</tr>
<tr>
<td>MBUGU BASALT 6</td>
<td>mature</td>
<td>fine texture</td>
<td>some landslides, grey patches white (kaolin (?), vegetation scarcity</td>
<td>reworked and breccias</td>
</tr>
<tr>
<td>NGALOA BASALT 1</td>
<td>mature-flat</td>
<td>flat area</td>
<td>conical hills, smooth surfaces, white-grey and flow structures</td>
<td>lava, pillow lavas and sedimentary rocks</td>
</tr>
<tr>
<td>NGALOA BASALT 2</td>
<td>mature</td>
<td>dendritic</td>
<td>tone grey to dark grey</td>
<td>sediments, lavas, pillow lavas</td>
</tr>
<tr>
<td>NGALOA BASALT 3</td>
<td>mature</td>
<td>dendritic</td>
<td>flow structure, lava tongues</td>
<td>lava, sediments, pillow lava</td>
</tr>
<tr>
<td>M'BENUTRA BRECCIA</td>
<td>immature</td>
<td>dendritic, rough texture</td>
<td>can be distinguished from T92 by flank slopes</td>
<td>lava, pyroclastic materials</td>
</tr>
<tr>
<td>NASARWANGGA P.</td>
<td>mature-flat</td>
<td>trellis, dendritic</td>
<td>no photographic lineament, white grey tone, smooth surface</td>
<td>tuffs, and breccias</td>
</tr>
<tr>
<td>ULUIYANDALI BASALT</td>
<td>medium</td>
<td>dome structure</td>
<td>radial drainage patterns</td>
<td>lava and breccias?</td>
</tr>
<tr>
<td>NAURA RHOLITES</td>
<td>mature</td>
<td>dendritic, some trellis</td>
<td>landslides, grey patches white large valleys</td>
<td>lava flows and pyroclastic materials</td>
</tr>
<tr>
<td>YUNAWAI VOLCANIC ROCKS</td>
<td>mature</td>
<td>dendritic</td>
<td>volcanic necks, faulting, folding</td>
<td>lava and pyroclastic?</td>
</tr>
<tr>
<td>NATUA FORMATION</td>
<td>mature</td>
<td>dendritic</td>
<td>topographic expression</td>
<td>sedimentary, lava flows, pyroclastic materials</td>
</tr>
<tr>
<td>NAKAYANGA FORMATION</td>
<td>mature</td>
<td>trellis, dendritic</td>
<td>fine texture, grey tone</td>
<td>breccias, sandstone, volcanic andesite</td>
</tr>
<tr>
<td>KOROLSVU TUFFS</td>
<td>mature</td>
<td>-</td>
<td>karst like topography, high topography, bedding layers</td>
<td>sediments, lava flows, and pyroclastic materials</td>
</tr>
<tr>
<td>RUKURUKU BASALT</td>
<td>mature</td>
<td>dendritic</td>
<td>rough textures, high topography</td>
<td>lava and pyroclastic materials</td>
</tr>
<tr>
<td>KAROMA FORMATION</td>
<td>mature</td>
<td>dendritic</td>
<td>grey tone</td>
<td>pyroclastic materials</td>
</tr>
<tr>
<td>INTRUSIONS</td>
<td>-</td>
<td>-</td>
<td>Topographic expression, radial drainage pattern</td>
<td>andesite, diorite and gabbro</td>
</tr>
</tbody>
</table>
so that erosion and deposition activity is less important.

3b. Photo-lithological unit description in Mbua and Monkey Face area.

The lithological units derived from the aerial photo-interpretation (Table 7) are as follows:

3. b.1. Alluvium.

This unit includes river deposits, beach sand dunes, and sometimes fan deposits and swampy deposits. The unit consists of sand, muds and gravels. The morphological characteristics of this unit are the flat surface associated with swamps, light photo tone, braided, deltaic and meandering rivers. The alluvium on the deltaic pattern has a dark tone and dense vegetation cover, while inland (meandering river) the alluvium can be recognised by curving flow lineaments and light tone.

The alluvium can be used to indicate past coast-line movements. At Mbua village the river forms deltaic features, it means that the coast-line has been uplifted; it is characterised by no alluvium on the beach. If the Mbua area had an irrigation system, it would be hard to recognise the alluvium boundary, because under cultivation the criteria would be obscured. But the morphology and texture of drainage pattern could help the interpretation.
3b. 2. Mbua Volcanic Group.

The Mbua volcanic Group which has compositions ranging from basalt, hawaiite to trachyte (Hindle, 1976), can be divided into 6 units of photolithology; there are Youngest Mbua basalt (Tb.1), Mbua basalt 2 (Tb.2) etc.. The division is based on morphology, drainage pattern, textures and photographic tone. These units are:

3b. 2.1. Youngest Mbua basalt (Tb.1).

This unit consists of Ndriti basalt (Coulson, 1971), occupying the Mbua caldera, Mbua conglomerate covering the western and southern parts of the Mbua volcano (Seatura, Hindle, 1976), and upper Mbua basalt which consists of flows and volcanic breccias, forming the outer part for the Mbua shield. The youngest basalts forms the western and eastern parts of the Seatura volcano.


The Ndriti basalt occupying the Mbua caldera, has many different compositions ranging from hawaiite to trachyte. It is a complex dyke swarm.

The dykes trend NNW (345°) and the dip is vertical (?). On the junction between Nanganda Creek and Lovu Creek (ca 1 km east of the Ndriti village) the dykes have many colours and complex structure. Volcanic breccia is found within the dykes in places eg. Nanggakei Creek, east of Ndriti village).
All the outcrops are intensively weathered, so it is difficult to obtain a good sample, except in a drill hole. Sporadic pyrite and chalcopyrite are found within the dykes.

The drainage of the Mbua caldera is "feather pattern", it can be explained by the weathering processes following the jointing pattern of rocks. Hindle (1976), suggested that the Ndriti basalt resulted from the late stage of volcanic activity and formed by caldera collapse, where the summit of the Seatura volcano fell down and the fractures of the volcanic cone were injected by late phase magmatic differentiates.

The Ndriti basalt is separated from youngest Mbua basalt by faults. Some facets can be seen along the eastern part of this unit which suggests faulting. Several remnants of a circular erosion features are interpreted as stocks, (see map 1).

3b. 2.1.b. Mbua conglomerate.

The polymict conglomerate exposed in the road cuts between the Mbua school and the Ndama school is interpreted as a channel filling on valleys within the Mbua basalt (Plate 6a and b). On a small, rounded hill near Naruwi village, the Mbua conglomerate lies below the youngest Mbua basalt flows, but in road cuts before the junction of Naruwi and Ndama, the channel fill structure is clearly exposed. Coulson (1971) interpreted an interfinger-ing contact between Mbua basalt and the Mbua conglomerate.
PLATE 6 A.

PLATE 6 B.
EXPLANATION PLATE 6

The Mbua conglomerate outcrops are intensely weathered. They are formed of polymict fragments and exposed on the road cut. The fragment sizes range from fine sand to boulder (1/16 cm to 50 cm in diameter).

PLATE 6 A: The weathered conglomerates still retain many structures, even weathered plagioclase (?) can be recognised (right corner). Rain allowed clear exposure of conglomerate on the drain road.

PLATE 6 B: Conglomerate exposed on the road cut between Mbua school and Ndama school. The fragments are not oriented or sorted, so that flow direction of the conglomerate cannot be determined.

PLATE 6 C: Conglomerate exposed on the road cut between Sawani and Tongalevu River on a gentle ridge of Tongalevu. The conglomerate overlies tuffs at a sharp boundary and dips about 5° - 10° to SSE.
The conglomerate was also recognised on the southern part of the Mbua volcano from this aerial photo study and later confirmed in the field. In the Tongalevu area near Sawani, the conglomerate lies above a fine-grained tuff with gentle dip (Plate 6c). This conglomerate is very weathered, so it is hard to determine the nature of fragments, but in the road cut between Saolo and Nakawakawa, it is clearly polymict and is intercalated with claystone, sandstone and carbonaceous shale.

The conglomerates weather to a yellowish brown to dark brown. The outcrop closest to Ndaria shows layers of different colour, and the boundary between the Mbua basalt and the conglomerate is marked by a colour change. The Mbua basalt is reddish brown in colour. The boundary is interpreted to occur about 1 km from the Ndaria village.

On aerial photographs the Mbua conglomerate forms a "bubbly" morphological feature distinctly different from the rounded, small hills where basalt covers it (outcrop near Naruawai village, Plate 7). The photographic tone of the Mbua conglomerate is white to light grey. Trees might have been cut down since the area has been inhabited, so in most areas, it is covered by sedge-grass.

Hindle (1976) suggested that the Mbua conglomerate was formed by fan deposits, where the materials came from the Ndriti basalt through a westward breach in the caldera Ndriti River gap. The discovery of conglomerates to the east does not negate this conclusion, but suggests that a
EXPLANATION PLATE 7.

"Bubbly texture" of the Mbuia conglomerate.

The Naruwei normal fault created a block faulting can be seen clearly under stereoscopic view. The Mbuia basalt 1 has "feather pattern" (f) and the Mbuia conglomerate formed a "bubbly texture" (Tbc).

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qa</td>
<td>Alluvium</td>
</tr>
<tr>
<td>Tbc</td>
<td>Mbuia conglomerate</td>
</tr>
<tr>
<td>Tbd</td>
<td>Ndriti Basalt</td>
</tr>
<tr>
<td>Tb 1</td>
<td>Mbuia Basalt 1</td>
</tr>
<tr>
<td>Tb 2</td>
<td>Mbuia Basalt 2</td>
</tr>
<tr>
<td>Tb 3</td>
<td>Mbuia Basalt 3</td>
</tr>
<tr>
<td>☞</td>
<td>Principal point</td>
</tr>
<tr>
<td>-----</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Photo-lineament</td>
</tr>
<tr>
<td>⩢ ⩢</td>
<td>Dip slope/triangular facet</td>
</tr>
<tr>
<td></td>
<td>Fault</td>
</tr>
<tr>
<td></td>
<td>Topographic scarp formed by normal fault</td>
</tr>
<tr>
<td>⩢ ⩢ ⩢ ⩢</td>
<td>Mbuia caldera rim</td>
</tr>
<tr>
<td></td>
<td>Lithological boundary</td>
</tr>
</tbody>
</table>
large part of the shield may have been mantled by conglomeratic erosion debris.

3b. 2.1.c. Mbua basalt 1 (Tb.1).

This unit generally produces a rough parallel and radial drainage pattern. In the west Mbua basalt 1 consists of mainly of lava and volcanic breccias and forms a "feather drainage pattern" and has dark to grey tone (Plate 7). Its morphology is due to rejuvenation, where cutting down is greater than lateral erosion. Seatura volcano is interpreted as having been uplifted on the southern side where coral reef and sand bars are found in front of Mbua Bay.

The distribution of Mbua basalt 1 on the southern coast of Seatura volcano forms a flat bench which is exposed at low tide.

3b. 2.2. Mbua basalt 2 (Tb. 2).

This unit covers the northern flank of Seatura volcano. Its drainage has a rough, trellis and dendritic pattern, with scanty or savannah vegetation tree cover. The morphology has rejuvenated resulting in mesa and flat smooth hills (near Savutumbui Falls). The end of some ridges, especially in the north, have the form of remnant lava tongues. The weathered soil is reddish brown with scattered rounded boulders on its surface.
The volcanic vent producing Mbua basalt 2 (Tb 2) is interpreted to lie on the summit of the water shed between Naruwi Creek and Navatuvalu Creek. This vent Tb 2 lies in immediate contacts with Ngaloa volcanic products, it might be possible that its flows reached the sea and formed pillow lavas. Weathered pillows can be seen in the road cut between Mbua school and Ravuravu Lake, lying above bedded sandstones.

3b.2.3. Mbua basalt 3 (Tb.3).

Mbua basalt (Tb.3) is distributed on the upper northern flank of Seatura volcano. The morphology is light undulating hills and has boulder fragment in front of every lava-tongue ridge. Vegetation cover is grass without trees on the western flank, and on the eastern it is covered by dense forest.

This unit can be separated from the Mbua basalt 2 by its morphology. Mbua basalt 3 forms low ridges instead of mesas, some of them covered by the Mbua Conglomerate. The drainage density indicates that Mbua basalt 3 is older than Mbua basalt 2.

3b.2.4. Mbua basalt 4 (Tb. 4).

Mbua basalt 4 can be separated from the other units by its fine drainage pattern, flat surfaces and its covering of small trees (Savannah) giving a light grey tone. This unit is distributed on the northeastern
flank of Seatura volcano where it flowed out a long distance. The rock colour in fresh outcrop is dark bluish green, and weathered rocks reddish brown.

On the eastern part of this unit, the Tb. 4 covers the Natewa unit which forms a window.

3b. 2.5. Mbua basalt 5 (Tb.5).

This unit is distributed eastward of Seatura volcano flank. It is characterised by landslides, vegetation cover of dense forest, medium drainage pattern and grey tone.

The lithological boundary between Mbua basalt 5 (Tb. 5) and other units is drawn following the main stream, where the topographic features and the morphology differ very sharply. The catchments of the main streams flowing northward and southward are located on this unit (Tb. 5).

3b. 2.6. Mbua basalt 6 (Tb.6).

This unit is characterised by flat surfaces, dense vegetation cover and some landslides at the southeastern part. At the northern part, the flows are covered by thin tuffs and no vegetation. Ponded lava flows reached 40 m in thickness (Naselesele Falls, Hindle, 1976).
Mbuia basalt 6 lies above the Nasarowangga Formation (Ta2), which consists of mudstone, siltstone, sandstone/tuff, marl and grit/lapillistone. The contact between these units can only be seen in the drill core at Naselesele (Hindle, 1976).

Columnar jointed flows of Tb. 6 produce a waterfall, where on the aerial photographs, it gives a long strip of white to light grey tone following the river. Naselesele falls is not recognised on the stereo-pairs, but the ponded lava flows forms a flat surface topography.

To the east of Seatura volcano, the landslides and flat topped hills can be recognised on the stereo-pair photographs on scale of 1:80,000.

On the published geological map (Map 2), the Mbuia basalt has only one unit with some intercalation layers, eg. tuffs, Naruwai basalt conglomerate, Lekutu mudstone, Ngaloa basalt and some sedimentary rocks (limestone, grit, breccias). On photogeological map (Map 1) the Mbuia basalt has been sub-divided into more units than on the published geological maps. The photogeological units represent morphology units rather than lithological units. It might be that the same lithology has different morphology, because of different local climates, structure and geographic location. It is considered more likely that the photogeological units represent different flow units developed in different segments of the shield volcano during its active build up.
3.b. 3. Ngaloa Zone.

The junction between the Monkey Face Volcanic Group and the Mbua Basalt Volcanic Group is marked by a zone of different photogeological characters. Ngaloa basalt from the north (Ngaloa Island and the north coast district) was recognised by Coulson (1971), as a different rock type from the Mbua basalt; a detailed description is given by Coulson (1971, p. 32).

Rickard (1966) placed the boundary between the Monkey Face Volcanic Group and the Mbua Volcanic Group at a morphological change where the rough and hilly surfaces of the Monkey Face Group changed to flat and sporadic rounded, small hills marking the remnants of the Mbua basalt plateau. Coulson (1971) placed the boundary further south from Rickard's boundary, since he included all the pillow lavas with the Monkey Face Volcanic Group.

Under the stereoscope the junction zone between these volcanic groups has a distinctive character. It is low land with a few rounded hills, its drainage pattern is dendritic and trellis; the photographic tone is light grey to grey, and the vegetation cover is grass and small trees (savannah).

The zone can be divided into 3 photogeological sub-units. Each sub-unit may have the same lithology (sedimentary rocks, flows and pillow lavas), but the character of the sedimentary rocks and flows is variable in each sub-unit, and provides a different morphological character.

The interpretation of the junction area can be summarised as
Ravuravu Lake is formed by damming the small river under the conical hill (H). The rockslide/landslide came from a small, circular, isolated hill (H). This hill is interpreted as a "hornito", where the Mbua basalt flows are usually ponded in the older relief (Naselesele Falls, Savutumbui Falls). The ponded lava flows are characterised by flat, smooth surfaces and sometimes they form a mesa (m) with gentle dip northward.

- Principal point
- Lithological boundary RB = Rickard's boundary
- CB = Coulson's boundary between Monkey Face Volcanic Group and Mbua Volcanic Group.
- Dip slope/triangular facet
- Fault
- Topographic scarp/rockslide/landslide
- Horizontal surface
- Dam
- Bedded layers

G - Gabbro (Coulson, 1971)
Tb 1 - Mbua basalt 1
Tng 1 - Ngaloa 1
Tng 2 - Ngaloa 2
Tmf 1 - Monkey Face 1
Tmf 2 - Monkey Face 2
Tmf 3 - Monkey Face 3
follows (Fig. 29):

1. Coulson's interpretation is based on the assumption that Mbua volcanic products are entirely subaerial, hence he includes the northern pillow lavas with the Monkey Face Volcanic Group.

2. Field checking showed that the flat sheets of pillow lavas are at the same topographic level as the columnar jointed sheets forming plateau and waterfalls, and the pillow lavas lie above steep (35°) dipping sediments. There is no reason why the Mbua lava flows could not have reached the sea and formed pillow lavas. This interpretation means that the junction zone is one of intermixture of layers of Monkey Face sediments and Mbua basalts.

One of the rounded hills is interpreted as a plug or vent at the Ngaloa zone (Plate 8). The hill is situated midway between Nasarowangga and Mbua school. Rockslides from this hill dammed the small river and formed Ravuravu Lake. At first sight the barrier was interpreted as a lava flow from the conical hill "vent", but a field check showed the surficial nature of the material. If this hill is a vent, it must be a "hornito" (Macdonald & Abbot, 1970).

In hand specimen the rock of that hill has coarse to medium grained crystals, porphyritic texture, dark green to dark blue on fresh sample and dark blue to yellowish brown on the weathered sample. Under the microscope it has phenocrysts mainly of plagioclase (labradorite - bytownite), olivine
Fig. 29. — Cross-section of NGALOA ZONE. MFVG = Monkey Face Volcanic Group; BVG = Mbua Volcanic Group; PL = pillow lava; V = vent like (Plate 8).

Scale

Vertical: 1: 12,500
Horizontal: 1: 50,000.

Hindle (1976) included in this group the Nasarowangga Formation, Mbenutha Breccia and the Nambuna Complex. The later consists of the Vutusunga Complex and the Ndavutu Lapillistone.

The Nararo Volcanic Group consists of mainly acid to basic andesite occurring as plugs, flow and reworked fragments of sedimentary rocks. One of the plugs (Namoi peak) is composed of brecciated basic andesite. Hindle suggested that the Namoi plug is rimmed by massive acid andesite and the plug is interpreted as the final stage of intrusion activity. The Nasarowangga Formation and the Ndavutu Siltstone are sedimentary rocks derived from Nararo products, ranging from marl to conglomerate.

On the photo-interpretation map (Map 1) the Nararo Volcanic Group can be recognised from its morphology, its tone and its drainage pattern. This group can be divided into 2 units, e.g. $T_a$ and $T_a \pm$ (Mbenutha breccia and Nasarowangga Formation).
PLATE: 9 - Mbenutha Breccia.

A. - Horizontally bedded breccia of the Mbenutha Breccia formed an isolated hill. Viewed stereoscopically, it can be easily mistaken for a plug.

B. - Hill in the eastern part of the Ndelanathau peak, once quarried for road metal. The rock crusher became a "fossil" of the quarry, where grass cover is very thick.
3.b.4.1. Mbenutha breccia.

The Mbenutha breccia (Ta1) forms a hilly terrain with some plug-like peaks on it. In fact, not all the hills are formed by intrusive rocks; although they appear under stereoscope as plugs, two hills are formed of horizontally breccia (Mbenutha hill and the one to the east of Ndelanathau peak, (Plate 9). The breccia fragments ranging from clay sized to a few metres of angular components, were quarried for road metal (Plate 9 and 10) to construct the timber access road.

The boundary of the Namoi brecciated basic andesite is not distinguishable under the stereoscope, but features such as a ring dyke and curving structures around the peak are visible.

The "triangular facets" interpreted from the photos between Namoi peak and Ndelanathau peak, do not exist. They are formed by different colour of vegetation exaggerated by stereoscopic view which led to their interpretation as triangular facets. Triangular facets are usually characteristic of faults in this area. The different colour of vegetation is caused by the soil fertility and the water content, which in term depends on the rock sources (Plate11).

3.b.4.2. Nasarowangga Formation.

The Nasarowangga Formation has a flat surface, grey tone and a trellis drainage pattern. It is hard to distinguish between the Nasarowangga Formation
Plate 10.

Plate 11.
PLATE : 10 - Mbenutha Breccia.

Photograph of the Mbenutha Breccia was taken on the quarry road between Nambavatu (Ndrekiti) and Soloa Levu. Clasts are of hornblende andesite, ranging from clay size up to more than 50 cm. The matrix has the same composition as the clasts (monomict breccia). The pencil length is about 20 cm.

PLATE : 11 - Triangular facet.

Photograph showing a false "triangular facet" formed by different colour of trees (dashed). On the stereo-pair the different colour of the trees form a "triangular like feature". The "triangular facet" is characteristic of faults in this area (usually normal faults). Photograph was taken from the Namoi peak looking toward the Ndelanathau peak (arrow).
and Mbua basalt 6 in places, because both have similar morphological features and drainage pattern. The distribution of the Nasarowangga Formation might extend to spread around the Mbenutha Breccia (Ta 1) and it also spreads to the southern part of the Vutusinga complex; but on the western part, it is covered by Mbua basalt. On the Wainunu River and its deeply incised tributaries, the Nasarowangga Formation facies (Ndavutu Lapillistone, Hindle 1976) is exposed, the tone is distinct and the vegetation sparse, but the size of the unit is unmappable from photographs and includes much Mbua basalt 6.


On Hindle's (1976) geological map, the Natewa Volcanic Group consists of the Ndreketi Andesite, Raviravi Volcanics Formation, Yanawai Volcanics, Navuturerenga Lapillistone, Valili Volcanics, Natua Formation, Naura Rhyolite, Nakayangga Formation, Thongea Lapillistone, Uluiyandali Basalt, and Kia dacites. The division is based on the volcanic facies and on composition,

On photogeological interpretation, the unit division which is based mainly on land form and morphology, is divided into 5 units. The units are Uluiyandali Basalt, (Volcano) Nakayangga Formation, Yanawai Volcanics, Naura Rhyolite and Natua Formation.

3.b.5.1. Uluiyandali basalt.

The Uluiyandali basalt forms a "dome like" structure, it has a marked
drainage pattern radiating from an isolated hill which stands above the Nakayangga Formation. Other hills with similar features are situated at Navutuvono Island and Nakayangga hill inland. The Uluiyandali Basalt has a chemical composition of sub-alkaline olivine basalt (Hindle, 1976). It is distinguished from the Mbua basalt by its finer texture and also by the fact that the top of Uluiyandali stands 120 m above the nearby Mbua basalt plateau.

3.b.5.2. Naura Rhyolite

The Naura Rhyolite has light grey tone (rare trees, because of infertile land) and occurs in a low valley. The boundary between the Naura Rhyolite and Yanawai Volcanics, is characterised by landslides whereas the boundary with the Natua Formation is faulted. On this eroded bareland, the Naura Rhyolite gives light grey tone with white stripes. The white lines were found to be layers of kaolin exposed below the lateritic crust. The kaolin has a variable thickness from 4 cm to 20 cm. The laterite covering the unit, is limonitic breccia with fragments between a few mm to 60 cm.

The outcrop in Naura Creek has a joint pattern with trends of 60°, 170°, and 200° and horizontal sheeting. A fresh sample is dark bluish green and forms a gently sloping topography.

3.b.5.3. Yanawai Volcanics.
The Yanawai Volcanics is characterised by light undulating morphology disturbed by some intrusions or plugs. Its drainage pattern differs from the Mbuas Basalt and the Nakayangga Formation. The stream pattern seems to follow in the volcanic flows rather than to cut the flow. The rock composition is basic andesite, but basalts, dacites and rhyolites also occur (Hindle, 1976).

Circular and radial faults are found surrounding Soloa Levu peak. Soloa Levu is an intrusive acid andesite (sample S.32). The Vutusinga complex intruded this unit along a volcanic lineaments (Plate 14). The photographic lineament trends NW and influences the drainage trend.

In the southern part of this unit, the flat topography with remnants of Mbuas basalt 6 as a "table land", does not show many photo lineaments. It might be that reworked material from the basalt covers the older volcanic here?

3.b.5.4. Natua Formation (Tn3).

The Natua Formation can be divided into 3 sub-units. The northern sub-unit covering the coastal area from Naduri westward (Thulasawani), forms a hilly ridge. Hindle (1976) called this unit Raviravi. Volcanics. The volcanic material consists of lava flow, breccia (with monomict fragments) and tuffs. The isolated outcrop of Thulawani is clearly seen under stereoscope. It has faulted NE trend and bedding dips between 20° to 30° SE.
PLATE 12 - NATUA FORMATION.

Photograph showing Natua Formation exposed on the road cut between Nambavatu and Soloa Levu. The beds have nearly horizontal dip, the differences of colours of soils might have different deformation. The layers have rounded fragment of andesite (more than 50 cm in diameter). Each bed composed of many cross-bedded, small layers ranging from \( \frac{1}{2} \) cm to 10 cm, which have different colour, grain size and dip.
The second sub-unit is in the Ndreketi Basin, where it is interpreted as volcanic materials derived from the northern and southern sub-units. They form low land along the Ndreketi river, which itself follows a big E-W fault. The topographic features are light undulating surface with some scarps on the boundary of the Raviravi Volcanics (northern sub-unit). The hill which is located near Ndreketi village, has a curved lineament and some faults trending N-S and NNW. It is interpreted as a "plug", where dome-like structure can be seen under the stereoscope (Koiroloma). In fact, the hill consists of coarse grained basaltic andesite in contact with tuffs. Hindle (1976) recognised a Ndreketi Andesite which has a N-S distribution trend, but he did not mention the possible vent. Under the stereoscope the Ndreketi Andesite is hard to trace, because this unit has a drainage pattern and morphology similar to the unit on its eastern side.

The third sub-unit is the southern part of the Natua Formation, which forms medium undulating terrain with topography higher than the Ndreketi basin. The source of the material is not yet known, but Hindle (1976) mentioned that the source for that volcanic product lies somewhere close to Utonitei peak. The main rock of this sub-unit is lapillistone which has some lava flows in it. This sub-unit is originally marine, formed by reworking volcanic materials. It has nearly horizontal bedding (Plate 12).

3.b.5.5. Nakayangga Formation.

The Nakayangga Formation which occupies the Southeastern part of the
central Vanua Levu, is characterised by light undulating morphology, some landslides, and the drainage pattern seems to be in a mature stage. Hindle (1976), mentioned that the boundary between the Yanawai Volcanics and the Nakayangga Formation gradationally changes. Under a stereoscope this unit is clearly seen as a bedded sedimentary rock; in some places $5^\circ$ slopes dip westward, but at Kumbulan Point on sheet No 11, a vertical dip of sedimentary rock striking E-W can be seen clearly under the stereoscope. The latter sedimentary rock seems to be older than the Nakayangga Formation.

Monkey Face Volcanic Group.

Coulson (1971) divided this group into the Karoma Formation, consisting of Korolevu Tuffs, Rukuruku Basalt and Karoma volcanic products. Under a stereoscope these units can be identified by their drainage pattern, their morphology and their lineaments.

Korolevu Tuffs have a "karst-like" topography, where a calcareous sandstone (?) remnant, forms an isolated hill (Plate 15). The lineaments of this unit trend NNW. A big fault trending NW can be recognised cutting this unit. The structure of this unit generally forms a syncline parallel to the big fault, (Plate 15).

Rukuruku Basalt consists of lava flows and volcanic breccia. On the stereo-pairs this unit is characterised by smooth rounded hills, medium undulating surfaces, and a dendritic drainage pattern. The annotation
on the aerial photograph is based on the tone, topographic level, and the drainage pattern.

A circular ridge with a gap to the southwest is interpreted as a vent for the Rukuruku Basalt; at the top of its peak is a sheeted lava flow of olivine basalt (sample No S.21).

The Karoma Formation which mainly consists of volcanic breccia and lava flows, has a large distribution on Monkey Face peninsula. It is characterised by dark grey tone, light to medium undulated surfaces, and has dendritic drainage pattern. The Karoma Formation has a mature stage of erosion. Few isolated hills are to be found to the north of Mbuu village. The contact between this formation and the Ngaloa basalt is clearly recognised both under a stereoscope and in the field. The Karoma Formation was originally a sub-marine volcanic product, so it is rather difficult to recognise the flow structures and the vent location. The distinctive characters of the Karoma Formation are the mature stage of its morphology and its savannah cover.

Conclusions of photo-interpretation of the Monkey Face Volcanic Group are:

1. A vent is interpreted somewhere near the Navandungu peak, where a horse shoe hill, eroded by Naithuvuti Creek, facing SW, has the photographic
feature of a crater. The vent interpretation is supported by the volcanic layers of the Monkey Face Volcanic Group dipping away of this point (Map 2). Other criteria indicative of a volcanic vent were not found, such as plug, radial and ring dykes and lava flows patches. Rickard (1966) suggested that the vent location is about 4 km further southwestward from the Navandungu peak, where a rough and gentle WSW dipping volcanic breccias is exposed.

2. The land form of the Monkey Face Volcanic Group suggests that this group is older than the Mbua Basalt Group. The interpretation is based on the rounded shape of hills with gentle slopes separated by shallow valleys and some meandering rivers. The river density in the Monkey Face area is higher than in the Mbua Basalt area. This interpretation is also supported by the discovered outcrop at the Savutumbui falls, where the sediments belonging to the Monkey Face Volcanic Group underlie the Mbua basalt. The Mbua Basalt land form is a large plateau incised by deep and narrow valleys.

INTRUSIONS.

A few intrusions were interpreted from aerial photographs, but some others shown on the published maps could not be seen on the aerial photographs, eg. Coulson's diorite near Koroinasalo and his gabbro near Ravuravu lake. The diorite does not appear as a plug on the photos, but it has more likely resulted from lithological interpretation; I could find no
evidence for it in the field similarly for the gabbro outcrop, where the
topographic feature and the structure surrounding the gabbro do not indi­cate an intrusion.

In tropical climate, the intrusives do not always form a positive
topographic feature, but sometimes erode quickly to form a low valley
surrounded by the country rocks. Gossan deposits may be a good indication
of intrusion.

4. Structural analysis.

In addition to the stratigraphic interpretation an attempt to de­termine the structural geometry was made by analysis of photo-lineaments,
fault patterns, coast-lines and the major distribution of volcanic centres
was examined to determine whether there was any relationship between them
and crustal structures.

4.a. Coast-line analysis.

The weathering and breaking of a rock mass is controlled by the
joints and other weaknesses in the rock. Physical energy (heat, cold and
mechanical power) breaks down the rocks through the joint pattern. Thus
the shape of an island formed of massive rocks is controlled by the joints.

The purpose of measuring the coastal lineaments is to determine the
Fig. 30. A. Rosediagram of coast-line elements of Vanua Levu. Scale: radius = 10, directions shown as proportion of maximum (see Table 11).

B. Vanua Levu island axis.
Fig. 31. Rosediagram of coast-line of Mbu area.
relationship between the jointing pattern of the island and the island shape. The length and direction of straight line segments of coastline were measured and the azimuths grouped into 10° intervals. The data plotted on a rosette diagram (Fig. 30, Table 7) can be explained as follows:

Four sets of lineaments are symmetrical about the direction of the island axis, these may be related to wrench directions about a stress system related to the island axis.

In West Vanua Levu (Mbuia area) the coastline trend diagram is somewhat different (Fig. 31) from that of Vanua Levu. The E-W trend is missing and a strong NNW trending set is developed. The differences might be due to the effect of the young intrusion and eruption of the Seatura volcano. The N-S trend parallels the Mbuia fracture in which the Seatura volcano erupted.

The northern coastline of the Undu and Monkey Face districts indicates submergence (Rickard, 1966). The coastline of both places is rough and several island remnants occur. At Mbuia and to the south, the coastline is smooth and some sandbars have been deposited on it, which indicates uplift activity is still going on. Thus the island with Seatura volcano may be tilting northward.

4.b. Photographic lineament analysis.
A 1:100,000 base map was used for plotting the photographic lineaments by conventional methods whereby the air photo annotations are transferred to the base map by matching the drainage and topographic features. Aerial photographs on a scale of 1:40,000 and 1:80,000 were used.

The photographic lineaments can be recognised under stereoscope by various features (Fig. 32):

a. Ellipse and narrow ridges within flat areas.

b. Scarp and triangular facet faces.

c. Elongated valleys associated with morphology.

d. Crossing ridges.

e. Elongated hills at the flank of ridges.

f. Topography scarps.

g. Valleys and ridges.

h. Zig-zag ridges.

In addition photographic tone can help in the recognition of lineaments in bare areas. Lineaments may be interpreted under binoculars on photo-pairs of scale of 1:40,000. Irregular (unusual) tones formed during the printing process are easily recognised by comparing the tones with an overlapping photograph.

The lineaments obtained from air photographs of Vanua Levu on scale of 1:40,000 and ones of 1:80,000, show at least 3 systems of lineament
- Ellipse and narrow ridges within flat areas
  Example: Run 5, no. 132, 133, and 134, Lambasa area.
  Run 4, 14 - 15

Scarp and triangular facet faces.
Ndriti River, run 7, 004, 005 and 006.
run 4, 086-085

• Elongate valleys associated with morphology
  Run 4, 068 - 067
  022 - 021
Crossing ridges.
Run 4, 094 - 095, 016 - 015.

Fig. 32d

Oval hills at the flank.
Run 4, 012 - 011.

Fig. 32e

Scarp of topography

Fig. 32f
Valleys and ridges
Run 5, no. 122 - 123

Zig-zag ridges
Run 4, no. 089 - 090

Fig. 32g

Fig. 32h

Fig. 32. Sketches of photo-lineaments manifested under stereoscopic view (Figure scale of 1:40,000, contour interval of approximately 1 metre).
Fig. 33. A. Rosediagram showing main trend of aerial photo-lineaments for Vanua Levu.

B. Rosediagram showing main trend of photo-lineaments of Mbu and Monkey Face area. Scale: radius = 10, directions shown as proportion of maximum (see Table 11).
trend. There are double conjugate sets nearly symmetrically disposed about the major NNW trending set (Fig. 33).

In the Mbuia and Monkey Face areas, a similar but more elongate pattern of lineaments were also observed. If the lineaments represent conjugate wrench faults then the indicator maximum principal stress was oriented ENE (Fig 33 b).

4.c. Drainage pattern analysis.

Weathering activity enhanced by chemical and physical processes, follows the weakness and jointing of the massive rocks. Thus the eroded drainage pattern should reflect the joint and fault systems of the rocks.

The drainage pattern obtained from segments of the rivers on Vanua Levu (measured on the 1:100,000 topographic maps), were plotted on a rose-diagram (Fig. 34). The drainage pattern trends reflect those of the photo lineaments, except that the different trends are more uniformly developed.

In the Mbuia area the drainage-pattern lineament systems have the same pattern as the rest of Vanua Levu (Fig. 34 b). The expected radial drainage of the young volcano seems not to affect the main trends.
Fig. 34. A. Rosediagram showing drainage pattern for Vanua Levu.
B. Rosediagram showing drainage pattern for Mbua area.
Scale: radius = 10, directions shown as proportion of maximum.
LEGEND PLATE 13

⊕ Principal point of photo No 18, run 5

--- Photographic lineament

↗ Dip slope/triangular facet

Fault; RF = Rickard's fault; PF = Photo-interpretation fault.

--- Lithological boundary; KB = Korotini Breccias

NP = Nasasa Pitchstones

EXPLANATION PLATE 13:

The youngest Lambasa fault, trending WNW was not recognised by Rickard (1966) or Ibbotson (1969). It has strong photographic lineaments and topographic relief. Rickard's fault running along the Mbu-thaisau River followed by Ibbotson, has a broadly straight valley trend­ing NNW.

The Korotini Breccias and the Nasasa Pitchstones (Ibbotson, 1968) can be recognised easily (under stereoscopic view). The Nasasa Pitch­stones are intensively fractured and show very fine photographic tex­ture with dendritic drainage pattern, whereas the Korotini Breccias have very rough photographic texture with trellis drainage pattern.

The geographical names were taken from Ibbotson's map (1968).
4.d. Faults.

The westerly trending set of faults are major features represented by Ndreketi fault which runs from Ndreketi village to Mbutha Bay, and another one running from the southern part of Lambasa to Vanuavoa in the Natewa Bay (Plate 13). The Ndreketi fault which on aerial photographs is a continuous lineament running some 70 km across the island is the longest fault found in Vanua Levu and is probably the youngest.

On the eastern part of Vanua Levu island, the fault trends differ from the western part (Rickard, 1966). On aerial photographs the lineaments of the eastern part are clearly seen (Plate 13), visible without stereoscope, with the major trend to the NE. On the western part of Vanua Levu the lineaments trend to the ESE parallel to Ndriti fault system, while others trend N-S (Naruwai fault, Mbua caldera, Monkey Face and Koroinasalo faults; Photogeological map).

Previous workers have mentioned these faults, except the one in the Mbua caldera and the one running from south of Lambasa to Vanuavoa.

In the Ndama area the Naruwai fault trending NNW is a normal fault with a very steep dip to ENE. On aerial photographs (Plate 7), the scarp formed by this fault is very clearly seen, but in the field, it seems to be marked by a small valley across which rocks are offset (the Mbua conglomerate and the Mbua flows).
Fig. 35. - Volcanic centre distribution in Vanua Levu (compiled from Rickard, 1966; Hindle, 1975; Coulson, 1971; photo and Landsat imagery interpretation).
Table: 8  Coordinate of volcanic centres measured from the 1:200,000 topographic map.

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Note: 1. Coastlines were measured on topographic map of scale of 1:200,000, figures in cm.
   2. Photo-lineaments were interpreted from aerial photographs of scale of 1:40,000 and 1:80,000, and plotted on base map of scale of 1:100,000, figures in cm.
   3. Drainage patterns were measured from topographic map of scale of 1:100,000, figures in cm.
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Note: 4. Volcano-spacings were measured on base map of scale of 1:200,000, figures in km
5. Faults were measured on photo-interpretation map on scale of ca 1:533,000, figures in cm.
A synclinal structure is interpreted to occur through the Naurore Bay (Plate 15), where the youngest unit of the Monkey Face Formation lies on the top of the valley with inwards dip. The syncline interpretation is based on the lithology and dip directions.

4.e. Volcano-spacing analysis.

Volcano centres identified by aerial photo-interpretation represent those that are indicated by lithology and topography, those indicated by lithology alone, those interpreted from volcanic necks and dykes, and those obtained from the literature (Fig. 35). Thus volcanic centres on this map represent all known remnant centres of magmatic activity. Volcanic centres were plotted on a 1:200,000 topographic map, and the centre coordinates were measured (Table 8). From these data the volcano-spacings on table 9 were calculated and the histogram of spacings was drawn (Fig. 36). The interpretation of the histogram is as follows:

- four peaks of volcano-spacing can be seen eg. 10, 25, 50 and 100 km; 25 km is the mode. Following Mohr and Wood (1976), the spacing suggests that the depth to the lithospheric magma source under these volcanoes was 25 km. The 10 km mode probably relates to an upper brittle crustal layer (Vogt, 1974). Rodda (1974) estimated the continental crust in Viti Levu is about 28.5 to 30.5 km, while Gill (1970) suggested a thickness of 35 km, to the source of basaltic magma under Viti Levu. There is no geophysical evidence for thickness of the crust under Vanua Levu, but the absence of
TABLE: 10,- VOLCANO-SPACING.

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Fig. 26 Histogram showing 3 modes of volcano spacing in Vanua Levu and Taveuni island. Inset major trends of volcanic centres.
Fig. 37. Volcanic clusters obtained from 56 centres (insert) in Vanua Levu and Taveuni.
Explanation of Fig. 38 and Plate 14.

Fig. 38. On aerial photographs some volcanic centres were interpreted in the Mbua caldera. The volcanic centre lineament trends strongly to the NNE., parallel to the major fracture of this area.

Fig. 38.b Volcanic centre lineaments in the Vutusinga complex (Cluster 3 on Fig. 37). Three major trends of lineaments were obtained, eg. WNW, NNW and ENE. Plate 14 shows the WNW trend which connects Namoi (?) – Ndelanathau, and NNW trend represents Nathangothango – Vutusinga 2 – and the southern peak of Ndelanathau.

Fig. 38c. The Taveuni volcanoes showing the strong lineament trend parallel to the island axis.
Fig. 38, A B and C. Scale: radius = 10, directions shown as proportion of maximum.

Principal point (photo No 117 run No 5A)

Dip slope/triangular facet

Vertical dip

Photographic lineament

Fault

Thrust fault

Volcano-lineament

Bedded Mbenutha Breccia forming positive topography

Plug forming a positive topography

EXPLANATION PLATE 14.

Vutusinga volcanic complex consists of Kalakala, Vutusinga, Nde-lanathau plugs and smaller hills within this area. Stereoscopically some hills of horizontal bedded Mbenutha breccia have topographical relief the same as the plugs. Thus, where it forms isolated hills the Mbenutha breccia is difficult to identify by photo interpretation.
TABLE 11.- Proportion of lineaments obtained from coastline analysis, photo-lineament analysis, drainage pattern analysis, volcano-spacing analysis, and fault analysis on the same magnitude. Maximum trend rated as 10.

<table>
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<th></th>
<th>280°</th>
<th>290°</th>
<th>300°</th>
<th>310°</th>
<th>320°</th>
<th>330°</th>
<th>340°</th>
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<th>10°</th>
<th>20°</th>
<th>30°</th>
<th>40°</th>
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<td>Coastline</td>
<td>6.0</td>
<td>8.6</td>
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<td>4.7</td>
<td>6.2</td>
<td>8.5</td>
<td>3.7</td>
<td>2.6</td>
<td>7.7</td>
<td>0.5</td>
<td>4.7</td>
<td>6.3</td>
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<tr>
<td>Photo-lineament</td>
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<td>9.0</td>
<td>5.8</td>
<td>6.8</td>
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<td>7.0</td>
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</tr>
<tr>
<td>Drainage pattern</td>
<td>8.2</td>
<td>6.5</td>
<td>6.8</td>
<td>6.6</td>
<td>9.2</td>
<td>8.5</td>
<td>6.4</td>
<td>6.6</td>
<td>10.0</td>
<td>6.8</td>
<td>4.6</td>
<td>3.9</td>
</tr>
<tr>
<td>Volcano-spacing</td>
<td>8.2</td>
<td>3.2</td>
<td>0.9</td>
<td>0.7</td>
<td>0.9</td>
<td>0.4</td>
<td>0.2</td>
<td>0.3</td>
<td>0.1</td>
<td>0.0</td>
<td>0.2</td>
<td>0.9</td>
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<tr>
<td>Faults</td>
<td>10.0</td>
<td>4.7</td>
<td>5.0</td>
<td>2.6</td>
<td>6.3</td>
<td>3.7</td>
<td>5.3</td>
<td>6.0</td>
<td>7.0</td>
<td>6.4</td>
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TABLE 11 — continued.

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<tr>
<th></th>
<th>50°</th>
<th>60°</th>
<th>70°</th>
<th>80°</th>
<th>90°</th>
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<td>Coastline</td>
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<td>5.3</td>
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<tr>
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<td>4.6</td>
<td>3.8</td>
<td>5.2</td>
<td>6.7</td>
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<tr>
<td>Drainage pattern</td>
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<td>6.4</td>
<td>4.3</td>
<td>6.9</td>
<td>8.8</td>
</tr>
<tr>
<td>Volcano-spacing</td>
<td>4.8</td>
<td>8.3</td>
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<td>7.9</td>
<td>10.0</td>
</tr>
<tr>
<td>Faults</td>
<td>3.5</td>
<td>1.2</td>
<td>1.2</td>
<td>2.6</td>
<td>7.3</td>
</tr>
</tbody>
</table>
Fig. 39 A. - Rosediagram of photo-interpreted faults showing two major fault trends (W NW and N-S), an ENE minimum trend coincides with Vanua Levu island axis.

Fig. 39 B. - Composite rosiagram interpreting analysis of coastlines, photographic lineaments, drainage patterns, and volcano-spacing.
Fig. 39. Diagram showing photo-interpreted faults (see explanation).

Scale: radius = 10. directions shown as proportion of maximum (see Table 11).
PLATE 15: Synclinal interpretation in Naurore Bay.

The eastern flank of synclinal limb has been eroded.

- Principal point
- Photo-lineament
- Fault
- Synclinal axis
- Dip slope/triangular facet
- Lithological boundary; Tmf3 = Karoma Formation; Tmf2 = Rukuruku basalts; Tmf1 = Korolevu tuffs
Pre-Miocene rocks and granites, suggest that the crust under Vanua Levu is younger and thinner than Viti Levu.

The centres were next tested for alignment using a Hough transformation (Fig. 37). The volcanic centres fall into 6 clusters. Each cluster can also be divided into sub-cluster, e.g. the Vutusinga cluster which has three sub-clusters each of which indicates a different trend (Plate 14), and Fig 38 b. The trends between volcanic centres are plotted as an inset on Fig 36. These show a major E-W trend and minor trends to ENE.

4.f. Structural interpretation of Vanua Levu (Fig. 40).

The structural interpretation of photo-lineaments, drainage pattern, coastline, volcano-spacing trend and faults are all very similar (see Table 11 and Fig. 39b). There is a marked symmetry about orthogonal sets. Major conjugate sets trending NW and NE could, if validly interpreted, as wrench fault directions imply that N-S maximum principal stress operated during volcanism and later tectonic activity. A secondary conjugate system is partly developed about the E-W axis, which might imply a change of stress axis from maximum to minimum in a N-S direction. The most remarkable feature of the combined plot is the lack of expression of the main island axis (Fig 39 b).

The fact that the volcano trends, major fault and joint controlled (?) photo-lineaments show such similarity, suggests that major crustal
fractures controlled the development of volcanic centres and continued to influence the accumulating intervolcano debris as they became lithified.
Table 12. Efficiency of aerial photographs of different scales.

<table>
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<tr>
<th>No</th>
<th>Aerial photograph scale</th>
<th>1:10,000</th>
<th>1:20,000</th>
<th>1:40,000</th>
<th>1:80,000</th>
<th>Landsat imagery 1:250,000</th>
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</thead>
<tbody>
<tr>
<td>1.</td>
<td>Regional structure</td>
<td>poor</td>
<td>fair</td>
<td>good</td>
<td>excellent</td>
<td>good</td>
</tr>
<tr>
<td>2.</td>
<td>Local structure</td>
<td>poor</td>
<td>fair</td>
<td>good</td>
<td>obscured</td>
<td>obscured</td>
</tr>
<tr>
<td>3.</td>
<td>Lithology</td>
<td>obscured</td>
<td>fair</td>
<td>good</td>
<td>poor</td>
<td>poor</td>
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<tr>
<td>4.</td>
<td>Vegetation (Forestry)</td>
<td>good</td>
<td>good</td>
<td>fair</td>
<td>poor</td>
<td>very poor</td>
</tr>
<tr>
<td>5.</td>
<td>Geometry/ as base map</td>
<td>good</td>
<td>good</td>
<td>fair</td>
<td>fair</td>
<td>good for large area</td>
</tr>
</tbody>
</table>
III. 5. Field checking.

Field checking was carried out in May 1979, after the photo-interpretation was made at the Australian National University, Canberra. The writer was supervised for part of the time by Dr M.J. Rickard and was assisted by Mr Taniela Nasua from the Mineral Resources Department, Fiji. The field work was carried out over 4 weeks. During the first week at the Mineral Resources Department office, the writer compared the data obtained from aerial photographs on a scale of 1:40,000 with those on 1:80,000. The result from those comparisons is:

1:80,000 aerial photographs are good for showing the regional structure and tracing the lithological units, whereas the 1:40,000 aerial photographs are efficient for plotting the location and detailed structural interpretation (Table 12).

The second week was used for checking the "plug like" structure near Ndreketi village (Koroilamo) and the intrusions of the Vutusinga complex. The intrusive nature cannot be proven in the field in many places, because of the thickness of the weathering and there is no river cutting the hill. Thus the "plug form" of Koroiloma is still suggested to be the vent feeding the Ndreketi andesite. On the Landsat imageries, the feature suggests a plug or a vent (Landsat imagery path 79, row 71, Fig. 23).

Many of the photo interpreted intrusions were not confirmed. The first one was the eastern peak of Ndelanathau, which consists of a horizontal
bedded breccia, and the second one was Mbenutha hill also composed of breccias. Those hills were interpreted as remnants, where fractures and faults have caused controlled topography. The breccias might flank dyke-like intrusions, however (Namoi peak). The topographic features of those hills is formed by steep walls which stand up above the medium undulating morphological unit. The sporadic hills to the north of Mbua village were found to be formed of volcanic breccia interlayered with lava flows, so that no plugs could be proven.

The third week was used to trace the Mbua conglomerate on the eastern and southern flanks of Seatura volcano. The Mbua Conglomerate was mapped by Coulson (1971) only on the western slope. The eastern deposits recognised for the first time in this photo study, were confirmed in the road cuts between Sawani and Ndaria.

The fourth week was spent checking the different lithological units of the Mbua Basalt. The lithological sub-division of the Mbua Basalt recognised on the photographs (photogeological map 1), could not be proven in the field, because the units have the same composition, and vegetation cover.

Some samples were taken for comparative petrological examination and thin sections were cut and studied to confirm the naming of rock units.
III. 6. - CONCLUSIONS.

The general volcanic geological configuration of Vanua Levu is well known from conventional mapping. Several volcanic centres of different ages and composition are linked by debris fans and infilling of sediment Basins. The present study revises the marginal boundary between the older Monkey Face Volcanic Group and the young Mbua Volcanic Group and indicates some internal sub-divisions within the major units. Some smaller plugs and vents are recognised, others shown on published geological maps are disputed.

The sub-divisions of Mbua volcanic cone in particular, may represent subsidiary overlapping flow tongues in different segments of the shield.

The late history of the Seatura caldera is complex. Ndriti basalt is considered older than Mbua basalt by Rickard, 1966 and Coulson, 1971, but Hindle (1976) placed this unit within the Mbua basalt, and thought it to represent late-stage altered rocks of the now exposed root-zone of the volcano. The latter is probably correct, but the problem cannot be solved from photo-interpretation or quick field checking.

A breach of the western side of the caldera yielded conglomerate as suggested by Hindle (1976), but since conglomerate were also found on the southeastern flank of Seatura cone, it suggests that conglomerate was deposited extensively as a flanking mantle around the whole cone.
Rickard's flat erosion surface with bauxite was not recognised by Coulson or Hindle, but on the photo-interpretation this feature was recognised in the southeastern part of Seatura shield, but not on the northern flank, where the flat surface forming the lower slope of the shield is made up of flat sediment and tuffs.

Study of coastline, photographic lineaments, drainage pattern, faults and volcano-spacing suggest that a fundamental fracture in the 25 km crust, controlled the volcanic development and continued to later in its history to impose similar structures on the consolidated volcanic debris. The major WNW fault trend is reflected in the volcanic distribution, but the volcano trend along the island axis is not reflected in the fault trends (cf. Fig. 36 and 40).
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<th>No.</th>
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<td>Volcano-spacing, fractures and thickness of the lithosphere; Earth Planet. Sci. Lett. 21, 1974, pp. 235 – 252.</td>
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<td>Volcano-spacings and lithospheric/crustal thickness in the Archean; Earth Planet. Sci. Lett.</td>
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