DENUDATION RATES IN NORTHEAST PAPUA FROM
POTASSIUM-ARGON DATING OF LAVAS

BRYAN P. RUXTON* and IAN McDOUGALL**

ABSTRACT. The Hydrographers andesitic strato-volcano in northeast Papua is in
a late Pleistocene residual mountain range of dissection, and the original surface
on the eastern flanks can be reconstructed by drawing generalized contours. The
amount of ground lowering of concentric sectors, distant from the center, has been
measured as the difference of the present cross-sectional areas of the sectors from
the original cross-sectional areas.

Potassium-argon dates of fresh massive lavas from near the original surface range
in age from 650,000 to 700,000 years.

Assuming an age of 650,000 years for the beginning of dissection of the volcano,
denudation rates range from 8 centimeters per 1000 years at a relief of 60 meters to 75
centimeters per 1000 years at a relief of 760 meters. These rates are similar to those
estimated by conventional methods in West Irian, Indonesia, the Philippines, Guate-
mala, and northeast Queensland in comparable hot-moist climates and hilly and
mountainous terrain.

INTRODUCTION

Denudation is the sum of the processes that result in the wearing down of the surface of the Earth, and rates of denudation are the rates
at which various portions of the Earth's land surface are worn down.

A land surface is denuded while it is being uplifted and so rates of
denudation differ from rates of surface lowering (or raising) by the
rate of tectonic uplift or subsidence.

Quantitative measurements of particular denudational processes
have often been made at specific sites, as of slope erosion in America
(Schumm, 1956) and of soil creep in England (Young, 1963). But it
has not yet proved practicable to measure and then sum the effect of
all the denudational processes at a site (for example, chemical weathering
and leaching, and subsurface erosion). Moreover, since denudational
processes rarely act uniformly either in space or time it is hazardous to
extrapolate the limited site data available to large areas.

Conventionally, rates of denudation are estimated indirectly by
two main methods: by measuring the amount of earth material trans-
ported by rivers from catchments of known area over short periods of
time (Dole and Stabler, 1909; and Judson and Ritter, 1964), and by
estimating the amount of sediment deposited in basins from inferred
areas of land over very long time periods (Gilluly, 1949; and Menard,
1961).

Modern refinements of isotopic dating techniques and the large
number of radiogenic dates now available provide the basis for addi-

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In northern Peru from Pisco-Rancho Churinga of coast 1
lats. 1958" and "1957 (U.S. Navy-McDougall-Duncan).
<table>
<thead>
<tr>
<th>Volume</th>
<th>Rock type</th>
<th>Sample number</th>
<th>Description</th>
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<td>1.65g</td>
<td>0.19g</td>
<td>Basal breccia</td>
</tr>
<tr>
<td>0.89g</td>
<td>0.59g</td>
<td>0.09g</td>
<td>Fault breccia</td>
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<td>0.59g</td>
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<td>0.51g</td>
<td>0.46g</td>
<td>0.05g</td>
<td>Tectonic slice</td>
</tr>
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</table>

Polysenoidal-die on some volcanic rocks from northeastern Peninsula.

Table 1
adventive cones, lava flows, and minor intrusions and are stratigraphically younger than the Hydrographers Volcanics. Four samples have been dated in this study (table 1) as a further check on consistency, and all yield dates that are younger than the lowest age of 0.56 million years found for the Hydrographers Volcanics. Samples 3 and 4 are massive trachybasalt intrusions which occur in the flanks of the older Sesa volcano. Sample 2 is from the Kawokoki lava cones which are younger than the stratigraphy overlie the lava from the Hydrographers volcano (sample 5) dated at 0.56 million years. Hence the age of 0.36 million years is consistent with the stratigraphy. Sample 1 is a trachyandesite from the Bu'a flow dome and yields the very young age of 0.079 ± 0.01 million years. This flow dome is little dissected and is regarded as very young.

From the consistency of the dating results with the stratigraphy for the Hydrographers Volcanics and the Uooivi Volcanics, it is believed that loss of radiogenic argon from the samples has not been important and that the measured dates probably approach the true ages closely. These data suggest that the final stage of construction of the Hydrographers Volcano was in progress between 0.65 and 0.70 million years ago, and an age of 0.65 million years is taken for calculating the rates of denudation. Owing to alteration the date of 0.56 million years for sample 5 is subject to large uncertainty and is not significantly different from the dates of samples 6, 7, and 8.

The Sesa volcano, which occurs at the southern margin of the Managalese plateau, is strongly eroded and has reached a near-skeletal stage of dissection (compare Kear, 1957). Hence on geomorphic grounds it is clearly older than the Hydrographers volcano; four age measurements have been made on samples from the Sesa Volcanics to determine the age. The volcano is built mainly of agglomerate with less common lavas and tuffs (Smith and Green, 1961; Ruxton, 1966). The dates on the four samples of lava selected range from 5.4 to 5.75 million years (table 1). Sample 14 is from a neck within the central part and probably one of the youngest rocks of the volcano. The measured date of 5.75 million years is regarded as very reliable because the rock was fresh and holocrystalline. This result may indicate that some radiogenic argon has been lost from the other samples, although sample 11 is also excellent for dating. The dates show that the Sesa volcano was constructed in mid-Pliocene time (Funnell, 1964) and provides quantitative confirmation of the conclusion reached on geomorphic arguments.

Reconstructions of the initial volcano form.—In the absence of topographic maps, aerial photographs have been used to study the form of the dissected volcano. A run of photographs, covering the highest peaks of the range eastward to the sea, was selected, and by using scale in vertical control a contour map was made photogrammetrically by the Division of National Mapping, Department of National Development, under the supervision of Mr. E.F.N. Seton.

To reconstruct the approximate original form of the volcano, generalized contours (see Miller, 1953) were drawn across the detailed contour map (fig. 3). These show a fairly symmetrical form in the eastern half of the map, but in the central area they tend to outline the major peaks and the large craters. In other similar studies the original surfaces of the flanks of the volcanic structure have been extrapolated upward into the central deeply dissected core (Wentworth, 1927; Solomon, 1964); but here the core is complex in having more than one crater, and similar extrapolations are not made from the superimposed profiles (fig. 3).

The presence of mature weathering profiles on the major radial ridge crests in the eastern half of the mapped area supports the view that the generalized contours are a close approximation to the original form of the volcano.

The amount of dissection of the volcano.—The assumption that the flanks of the original volcano were symmetrical in form without deeply dissected valleys is based on the forms of Mounts Victory and Lamington, similar but active strato-volcanoes 80 kilometers (50 miles) to the east and 25 kilometers (16 miles) to the west of the Hydrographers range respectively. The flanks of these volcanoes have closely spaced sub-parallel streams incised only 10 meters (30 feet) to 60 meters (200 feet) below the general surface (see Kwin, Higatura, and Hamamatsu land systems, Haantjens and others 1964a,b). The summit areas of these active volcanoes are irregular with several volcanic land forms of recent eruption centers with local relief of up to 300 meters (1000 feet), and the Hydrographers volcano was probably similar irregular in its central area.

Assuming the processes of construction were complete before deep dissection began and the cone flanks had an originally symmetrical form, the amount of lowering of each concentric sector, distant from the center, can be measured graphically by the difference of the present cross-sectional area from the original cross-sectional area (divided by the length of the section) obtained from the topographic map and the generalized contour map respectively.

On the eastern flanks of the volcano such sections were drawn parallel to the general direction of the generalized contours from 61 meters (200 feet) to 975 meters (3200 feet). Each section was divided into major and minor ridges, the latter representing planezes on the lower flanks, and separate calculations made of the relative amount of land lowering (fig. 4). In the center of the volcano only rough estimates were made of the amount of land lowering from several sections drawn east-west and north-south across the topographic map.

Terrain parameters.—On each section of each section measurements have been made of available relief and the average maximum slope, and from these the average slope length has been calculated.
The available relief is defined as the vertical distance between the major ridge crests and the adjacent major valley bottoms, and several readings (usually four) have been averaged to give a value for each sector of each section (fig. 4 and table 2).

The average maximum slope has been obtained from the trace of each section on the topographic map. For each sector the shortest horizontal distances were measured on each major slope over a vertical inter-

<table>
<thead>
<tr>
<th>Section parallel with</th>
<th>Amount of lowering (feet)</th>
<th>Average denudation rate feet/100 cm/1000 yr</th>
<th>Present relief m</th>
<th>Average maximum slope as gradient</th>
<th>Calculated average slope length m</th>
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<td>172 (52)</td>
<td>0.26 (7.9)</td>
<td>203 (62)</td>
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<td>280 (85)</td>
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<td>226 (69)</td>
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<td>390 (119)</td>
<td>0.60 (18.3)</td>
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<td>500</td>
<td>435 (132)</td>
<td>0.66 (20.1)</td>
<td>401 (122)</td>
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<td>973 (296)</td>
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<td>2555 (767)</td>
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<td>1002 (305)</td>
<td>1.54 (46.9)</td>
<td>1730 (532)</td>
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<td>1106 (356)</td>
<td>1.70 (51.8)</td>
<td>1730 (532)</td>
<td>1:1.0</td>
<td>2498 (758)</td>
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</table>

Minimum* 800 1.23 (37.5) 1500
Maximum 1600 2.46 (75.0) 2500**

* Estimates only, of volcanic core.
** Maximum relief is 3000 feet (914 m), but 500 feet (153 m) of this is thought to be due to original irregularities.
Denudation rates of the Hydrographers Range.—Assuming an age of 650,000 years for the beginning of dissection of the volcano, the rates of denudation are calculated and tabulated with the terrain data in Table 2.

The undissected volcano had an increasing potential relief from near zero at the periphery to probably 2000 meters (6560 feet) at the center. The present relief is less than the potential relief by an amount equal to the sum of the height above sea level of the major stream beds and the height below the original surface of the ridge crests. Thus inward from the sea the rates of denudation increase from 8 centimeters (0.26 feet) per 1000 years at a relief of 61 meters (200 feet) to 52 centimeters (1.70 feet) per 1000 years at a relief of 533 meters (1750 feet). There is a linear correlation between the rate of denudation and the relief (fig. 5A), the average maximum slope angle (fig. 5B), and the average slope length (fig. 5C). The relief in the central portions of the volcano attains a maximum of 914 meters (3000 feet) but only about 762 meters (2500 feet) of this is due to denudation. By extrapolating from Figure 5A the rate of denudation at a relief of 762 meters (2500 feet) is expected to be between 70 and 80 centimeters (2.3–2.6 feet) per 1000 years which is similar to that calculated from the estimate of ground surface lowering of 488 meters (1600 feet) in the volcanic center (Table 2).

Marine Denudation.—The lowest slopes of the eastern flanks of the volcano have been eroded by marine erosion, and several benches below 92 meters (300 feet) probably represent marine denudation during Pleistocene sealevel fluctuations. This cliffing explains the unusually steep slopes measured on the 61-meter (200 feet), 92-meter (300 feet), and other sections, and the anomalous points on the graph of denudation rates against average maximum slope gradients (fig. 5B). Similarly the widening of the valley floors near the coast is probably due to marine denudation, and parts of the valley flats may overlie buried channels.

DISCUSSION

Ash-Fall Layers.—In the last 90,000 years 7.5 to 15 meters (25 to 50 feet) of airborne ash has fallen on the eastern and central part of the Hydrographers Range from Mount Lamington. Thinner falls have also come from Mount Victory and the volcanoes of the Managalas Plateau (Ruxton, 1966a). The thickness of total ash-falls from other volcanoes is only a small fraction of the general ground lowering of the Hydrographers Range, and so it has been ignored in the calculations.

Denudation rates in comparable areas.—Denudation rates calculated from the load transported by rivers from catchment areas of varying size in mountainous areas of the humid tropics range from 27 centimeters per 1000 years (northeast Queensland, Douglas, ms) to up to and over 100 centimeters per 1000 years (Indonesia, Rutten, 1938; Philippines, van Bemmelen, 1949; Guatemala, Corbel, 1959), and Lam’s (1945) rough

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Fig. 5. Average rates of denudation plotted against (A) relief, (B) average maximum slope, and (C) average slope length. Data from the more dissected sectors is shown as closed circles, that from less dissected sectors is shown as open circles, and the cross at the top right hand corner in (A) is the datum from a rough estimate of the maximum amount of lowering in the volcanic center.
West Irian would not differ greatly from a general average.

Fournier (1960) claimed that erosion (sediment yield) is related to climate (precipitation) and relief, and he predicted an erosion rate of from 38 to 76 centimeters per 1000 years for New Guinea (1960, pl. 15). This range corresponds closely with the denudation rates of those parts of the Hydrographers Range with a present relief of over 305 meters (1000 ft).

**Denudation rates and terrain parameters.**—For similar lithology, climate, and drainage basin area, sediment yield (sediment outflow, Glyph, 1954) is believed to be a function of the angle (Lustig, 1965) and the length of slope (Musgrave, 1954), and also of relief (Schumm, 1954).

In this study the relief and climate both vary from the core to the periphery of the volcano, and only lithology is constant. Moreover the relief, slope gradients, and slope lengths have been progressively changing over the last 500,000 years as the original surface has been dissected to the present form. Therefore correlations between the calculated denudation rates and the present terrain parameters will be valid only if the present denudation rates are similar to those averaged over the last 500,000 years.

The linear relationship between the calculated denudation rates and the present local relief and the comparability of the results with those of similar humid tropical areas suggests that the calculated denudation rates probably bear a simple relationship to the present denudation rates. Schumm (1968) found that denudation rates increase as an exponential function of the drainage basin relief (the difference between the highest and lowest points in the basin), but he considered reliefs up to 9000 meters (30,000 feet). The part of his curve (1968, fig. 2) between 0 and 1520 meters (5000 feet) is practically a straight line.

**Erosionally graded land forms and denudation rates.**—In most mountainous landscapes in northeast Papua the ridges and ravines are of erosional type (Ruxton, 1967) with straight slopes generally averaging about 37°; and this slope gradient seems to be the local variations of relief, climate, and lithology.

In the Hydrographers Range similar equilibrium land forms occur only in the relief range of from 245 meters (800 feet) to 365 meters (1200 feet) where calculated denudation rates range from 25 centimeters to 45 centimeters (0.8 to 1.5 feet) per 1000 years. In areas with greater relief, in the headwater regions, the land forms are ungraded with rapid stream incision, and the slopes average (maximum average) up to 50°. The predominance of mass movement in the slope denudation processes leads to maximum denudation rates. In some areas of low relief, on the lower flanks of the volcano, the slopes become less steep as the streams approach base level. The slopes are concavo-convex, and the average maximum

**ACKNOWLEDGMENTS**

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**REFERENCES**


1. (GA 1454): Trachyandesite of Uoiv Volcanics. 9°8' S, 148°27' E. From south side of lava dome southwest of Uoiv at about 780 meters (2550 feet) altitude. Phenocrysts (8 percent) of augite and subordinate oxyhornblende, oxihornblende, and interstitial clinopyroxene and olivine, occur in a fine grained groundmass of plagioclase, pyroxene, and olivine. The rock is fresh.

2. (GA 1545): Alkalai basalt of Uoiv Volcanics, 9°8' S, 148°26' E. From massive lava flow in the Wallis group of islands. Phenocrysts of plagioclase, clinopyroxene, and olivine, occur in a fine grained groundmass of plagioclase, pyroxene, and olivine. The rock is fresh.

3. (GA 1135): Trachybasalt of Uoiv Volcanics. 9°8' S, 148°29' E. From sill in Senegalese Volcanics at about 250 meters (750 feet) altitude. Phenocrysts of augite, olivine, and interstitial clinopyroxene. The pyroxene is slightly altered.

4. (GA 1154): Trachybasalt of Uoiv Volcanics. 9°8' S, 148°31' E. From sill in Senegalese Volcanics west of Geomega at about 280 meters (900 feet) altitude. Phenocrysts of augite and olivine, and interstitial clinopyroxene. The pyroxene is slightly altered.

5. (GA 1942): Latite of Hydrographers Volcanics. 9°12' S, 148°22' E. From thick massive lava flow exposed near the summit of the Senegalese Volcanics. Phenocrysts of plagioclase, pyroxene, olivine, and interstitial altered material. This rock is fresh for dating purposes.

6. (GA 1488): Dacitic basalt of Hydrographers Volcanics. 9°00' S, 148°23' E. From thick massive lava flow exposed near the summit of the Senegalese Volcanics at about 1158 meters (3500 feet) altitude. Phenocrysts of plagioclase, augite, and olivine. The rock is fresh.

7. (GA 1490): Basaltic diorite of Hydrographers Volcanics. 9°06' S, 148°22' E. From massive lava flow in the Senegalese Volcanics at about 1610 meters (5280 feet) altitude. Phenocrysts of plagioclase, augite, and olivine. The rock is fresh.

8. (GA 1498): Latite of Hydrographers Volcanics. 9°00' S, 148°23' E. From massive lava flow exposed near the summit of the Senegalese Volcanics at about 1830 meters (6000 feet) altitude. Phenocrysts of augite, olivine, and interstitial altered material. This rock is fresh.

9. (GA 1487): Dacite diorite of Hydrographers Volcanics. 9°00' S, 148°23' E. From thick massive lava flow exposed near the summit of the Senegalese Volcanics at about 1610 meters (5500 feet) altitude. Phenocrysts of augite, olivine, and interstitial altered material. This rock is fresh.

10. (GA 1487): Dacite diorite of Hydrographers Volcanics. 9°00' S, 148°23' E. From massive lava flow exposed near the summit of the Senegalese Volcanics at about 1830 meters (6000 feet) altitude. Phenocrysts of augite, olivine, and interstitial altered material. This rock is fresh.

11. (GA 1487): Latite of Sesara Volcanics. 9°15' S, 148°28' E. From massive lava flow in the Senegalese Volcanics west of Barijil at about 700 meters (2200 feet) altitude. Phenocrysts of plagioclase, clinopyroxene, olivine, and interstitial altered material. This rock is fresh.

12. (GA 1487): Leucite basalt of Sesara Volcanics. 9°14' S, 148°28' E. From massive lava flow in the Senegalese Volcanics west of Barijil at about 235 meters (750 feet) altitude. Phenocrysts of plagioclase, clinopyroxene, and olivine. This rock is fresh.

13. (GA 1487): Leucite basalt of Sesara Volcanics. 9°15' S, 148°30' E. From massive lava flow in the Senegalese Volcanics west of Barijil at about 150 meters (500 feet) altitude. Phenocrysts of plagioclase, clinopyroxene, and olivine. This rock is fresh.

14. (GA 1487): Latite of Sesara Volcanics. 9°14' S, 148°29' E. From massive lava flow in the Senegalese Volcanics west of Barijil at about 180 meters (600 feet) altitude. Phenocrysts of plagioclase, clinopyroxene, and olivine. This rock is fresh.

15. (GA 1487): Latite of Sesara Volcanics. 9°15' S, 148°30' E. From massive lava flow in the Senegalese Volcanics west of Barijil at about 120 meters (400 feet) altitude. Phenocrysts of plagioclase, clinopyroxene, and olivine. This rock is fresh.

16. (GA 1487): Latite of Sesara Volcanics. 9°14' S, 148°29' E. From massive lava flow in the Senegalese Volcanics west of Barijil at about 180 meters (600 feet) altitude. Phenocrysts of plagioclase, clinopyroxene, and olivine. This rock is fresh.