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

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ABSTRACT. The Hydrographers andesitic strato-volcano in northeast Papua is in a late planeze-early residual mountain stage 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, Guatemala, 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 transported 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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tional methods of assessing denudation rates. For if in dissected landscapes earlier or "original" forms can be reconstructed and dated, then by measuring the volume of material removed denudation rates can be computed. Three types of original landscape which have relatively smooth, even surfaces and may sometimes be dated are erosion surfaces, newly emerged or upraised surfaces, and volcanic land forms.

Despite the abundant reconstructions of former erosion surfaces and levels from scattered remnant surfaces, relatively few such surfaces can be accurately dated. Even so it is surprising that geomorphologists have not used this data to calculate denudation rates. King (1953) estimated that major cyclic erosion scarps in several continents retreat at a rate of 30 centimeters in from 150 to 300 years, and if the length and average height of such scarps are known within specific areas a rate of denudation could be calculated. Similar remarks also apply to newly emerged land forms such as coastal plains and fold or fault uplifts such as anticlines or horst blocks.

Wentworth (1927, p. 117) used dissected volcanic land forms in quantitative erosion studies in Hawaii because of the "readiness with which the original form of the land may be reconstructed". Large volcanic structures retain portions of their original form for relatively long peiods, and many Lower to Mid-Pleistocene volcanoes are in a stage of late planeze or early residual mountain development (Kear, 1957). Isotopic dating techniques now allow dating of fresh massive lavas or of specific phenocrysts, such as sanidine or biotite, to ages of less than one million years which is within the time range of many surviving volcanic land forms, and the Hydrographers andesitic strato-volcano in northeast Papua is taken as an example.

Ruxton has been responsible for the sections on denudation and the field work; McDougall has carried out the potassium-argon dating and has contributed to the sections on dating and to the rock descriptions given in the appendix.

THE HYDROGRAPHERS STRATO-VOLCANO

The Hydrographers Range, rising from sealevel to 1887 meters (6190 feet) in northeast Papua (fig. 1), is a Pleistocene andesitic strato-volcano in a late planeze-early residual mountain stage of dissection. The average annual rainfall probably varies from about 2250 millimeters at sealevel to over 3000 millimeters above 1000 meters. The mean annual temperature varies from about 28° to 16°C from sealevel to 2000 meters, and there is little seasonal variation. Apart from man-made grasslands on the planezes near the coast the vegetation is a mature rain forest with lower and more open canopies at higher altitudes.

Geology.—The volcano is built almost entirely of interbedded ash, agglomerate, and lava ranging in composition from olivine basaltic doreite to dactic doreite (Ruxton, 1966b), and the commonest rock type is a hypersthene-augite-potash rich andesite (doreite). In general, these

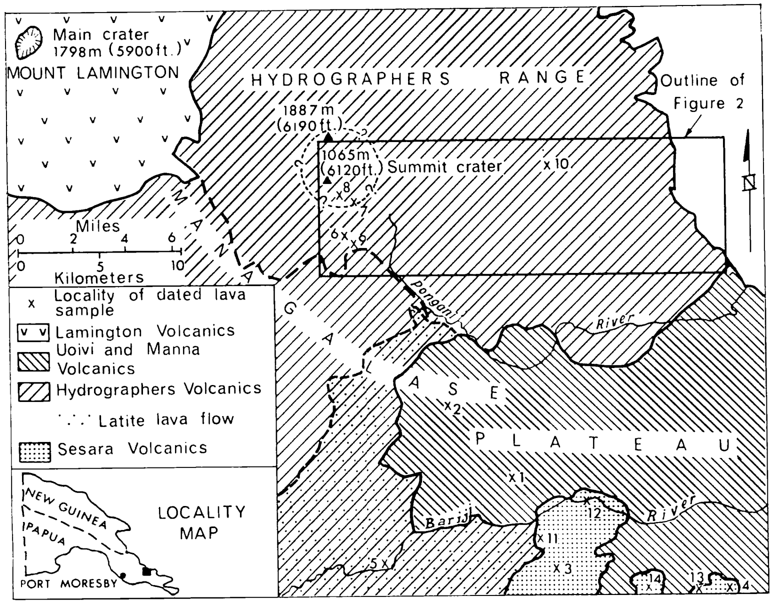


Fig. 1. Location map of the Hydrographers Range showing the localities of the dated lavas and the outline of the aerial photograph strip photogrammetrically contoured.

beds have gentle dips away from the center of the volcano, and there is no sign of faulting, tilting, or uplift, or other disturbance of the general structure.

Local adventive volcanism has occurred since the beginning of deep dissection of the strato-volcano, and the scattered small cinder cones and lava flows are of trachybasalt, basaltic latite, and dacitic doreite composition (fig. 2). These belong to the late Pleistocene to Recent volcanic suite (Uoivi and Manna Volcanics) of the Managalase plateau adjoining the southeastern sector of the Hydrographers volcano (Ruxton, 1966b).

Land forms and weathering profiles.—The Hydrographers volcano is roughly circular in plan. On the flanks, particularly in the east, little dissected triangular sectors (planezes, Cotton, 1952) occur between deeply incised consequent streams. These give way upward and inward to radially arranged accordant mountain ridges with mature weathering profiles preserved on their crests.

The central portion of the volcano has a broken pattern of mountain ridges and peaks without accordance and with only shallow immature brown clay soils on the very steep slopes and crests. The mature weathering profiles have an upper zone, 1.5 to 7.5 meters (5 to 25 feet) thick, of red, yellow, or brown silty clay overlying a lower zone of from 15 to 30 meters (50 to 100 feet) of varicolored clayey silt which has the texture of the parent rock preserved. Further details of the land units of this range are given in Haantjens and others (1964b) and

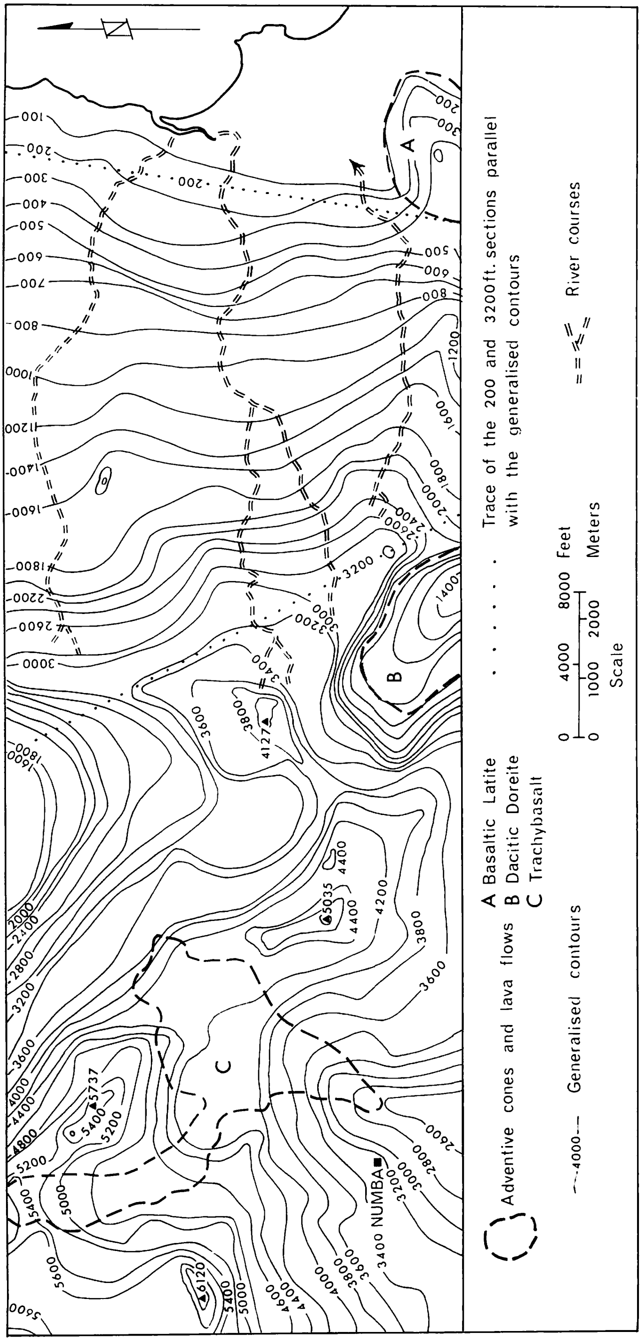


Fig. 2. Generalized contours in feet of part of the eastern flanks of the Hydrographers Range.

Ruxton and others (1967) in descriptions of the Hydrographers (mountain ridge) land system and the Banderi (planeze) land system.

Potassium-argon dating.—Selected whole rock samples of volcanic rocks from the Hydrographers Volcanics, the younger Uoivi Volcanics, and the older Sesara Volcanics to the south were dated by the potassium-argon method. Argon was determined by isotope dilution, and potassium by flame photometry according to the techniques previously described (McDougall, 1964, 1966). The results are listed in table 1. The precision of the age measurements is controlled mainly by the precision of the argon determinations. For air corrections of less than 70 percent in the argon runs the reproducibility of the measurements generally is better than 5 percent (table 1). For larger air corrections the uncertainty increases because of error magnification. Estimates of error at the 95 percent confidence level are given for each date in table 1.

To obtain reliable results on whole rock samples it is desirable to use holocrystalline, unaltered specimens to minimize the possibility of loss of radiogenic argon by diffusion. However, most of the rocks from this area, although showing little alteration, contain appreciable amounts of very fine grained to cryptocrystalline material in the groundmass (see brief petrographic descriptions in the app.); hence care must be exercised in evaluating the results, because argon loss may have occurred. In all cases the dates are reliable minimum ages, and the validity of the results must be assessed in terms of consistency with the stratigraphy.

The dating results from the Hydrographers volcano are fully consistent with the stratigraphic evidence. Sample 5 was collected from a very widespread latite lava flow which is believed to have erupted from the central crater during the final stages of activity. Hence the measured date of 0.56 ± 0.06 million years for this sample provides an estimate of the time at which the main activity of the volcano ceased. Because of the altered nature of this rock (see app.) reflected in the high air argon contamination, this date must be regarded as a minimum age.

Samples 6, 7, and 8 were collected from close to major ridge crests, where mature weathering profiles were thin or absent, from altitudes of 1158 meters (3800 feet), 1610 meters (5280 feet) and 1830 meters (6000 feet) respectively (fig. 1) and are probably about 153 meters (500 feet) beneath the original surface of the volcano. The equivalence in age of these three samples is well substantiated by the dating measurements (table 1). Sample 9 was obtained near the crest of a subordinate ridge, probably about 244 meters (800 feet) below the original surface of the volcano, and the older indicated age (0.78 m.y.) is consistent with this view. Sample 10 was collected from a boulder in an agglomerate bed at the base of a stream cliff at 183 meters (600 feet) above sealevel on the eastern flanks of the volcano and is some 266 meters (1200 feet) below the original surface of the volcano. The date of 1.45 million years found for this rock is consistent with its stratigraphic position, but the much older age may also indicate that it was derived from an earlier volcano.

TABLE 1

Potassium-argon dates on some volcanic rocks from northeast Papua

Sample number	Laboratory Number (Australian Natl. Univ.)	Rock type	K (%)	$^{40}Ar^{*}/^{40}K$ x 10^{-5}	% atmospheric ^{40}Ar	Calculated age (m.y.)	Rock series
1	GA 1544	Trachyandesite	2.566)				Uoivi
			)2.564	0.461	87.3	0.079 ± 0.01	
			2.562)				Volcanics
2	GA 1545	Alkali basalt	0.812)				
			)0.817	2.11	85.5	0.36 ± 0.04	
			0.821)				
3	GA 1133	Trachybasalt	2.106)	(1) 2.03	73.9	0.343)	
			)2.097			)0.355 ± 0.015	
			2.089)	(2) 2.14	62.7	0.366)	
4	GA 1134	Trachybasalt	1.289)				
			)1.290	2.57	78.9	0.44 ± 0.04	
			1.291)				
5	GA 1492	Latite	3.081)				
			)3.085	3.29	88.3	0.56 ± 0.06	Hydrographers
			3.090)				
6	GA 1488	Doreitic basalt	1.602)	(1) 3.90	56.6	0.67)	Volcanics
			)1.602			) ± 0.03	
			1.602)	(2) 3.91	49.0	0.67)	
7	GA 1490	Basaltic doreite	1.658)				
			)1.659	3.93	48.3	0.67 ± 0.04	
			1.661)				

8	GA 1489	Doreite	1.901 1.904	1.903	4.02	51.0		0.69 ± 0.04	Hydrographers
9	GA 1487	Dacitic doreite	1.674 1.684 1.699	1.685	(1) 4.64 (2) 4.51	55.5 41.1	0.80 0.77	0.785 ± 0.04	Volcanics
10	GA 1132	Latite	2.712 2.714	2.713	8.58	50.8		1.45 ± 0.08	
11	GA 1483	Latitic basalt	3.234 3.241	3.273	(1) 31.9 (2) 31.4	50.7 55.0	5.44 5.36	5.40 ± 0.2	
12	GA 1484	"Leucite basalt"	3.843 3.848	3.845	32.2	75.2		5.49 ± 0.3	Sesara
13	GA 1485	"Leucite basalt"	3.558 3.547	3.552	32.7	75.6		5.57 ± 0.3	Volcanics
14	GA 1486	Latitic picrite	2.191 2.204	2.196	33.6	10.0		5.75 ± 0.2	

$\lambda_k = 0.585 \times 10^{-10} yr^{-1}$ $\lambda_\beta = 4.72 \times 10^{-10} yr^{-1}$ $^{40}K = 1.19 \times 10^{-2}$ atom percent

Ar* radiogenic argon

The Uoivi Volcanics regarded as of Late Pleistocene to Recent form 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 Sesara volcano. Sample 2 is from the Kawowoki lava cones which stratigraphically 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 Bua 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 Uoivi 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 stages of construction of the Hydrographers Volcano were 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 Sesara volcano, which occurs at the southern margin of the Managalase 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 Sesara Volcanics to determine the age. The volcano is built mainly of agglomerate with less common lavas and tuffs (Smith and Green, 1961; Ruxton, 1966b). 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 is 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 Sesara 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,[1] covering the highest peaks of the range eastward to the sea, was selected, and by using sealevel for vertical control a contour map was made photogrammetrically by the

[1] Pongani run 1, 5037-5043, taken by Adastra on August 16, 1961, with a 152.70 millimeter lens from 7620 meters (25,000 feet). Scale at sealevel is 1:50,000.

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. 2). 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 larger reentrants. 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 had 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 Hamamatu 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 similarly 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 sector 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.

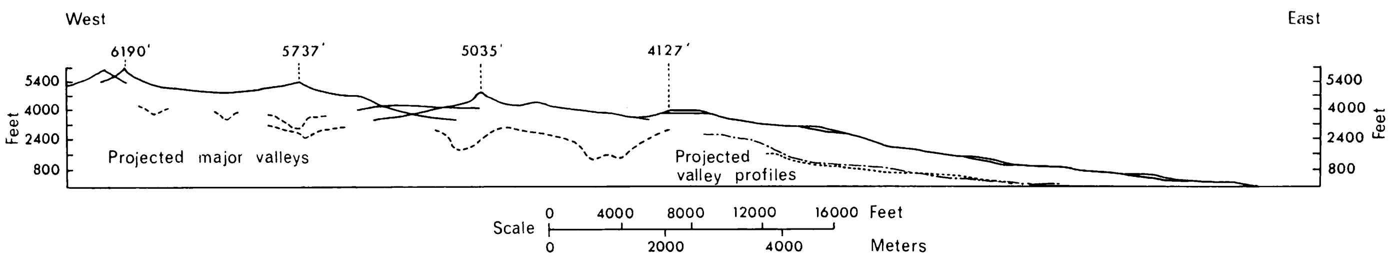
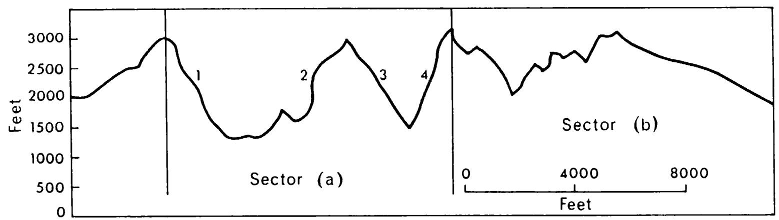


Fig. 3. Superimposed and projected profiles of the original surface and the present valley bottom from the center of the volcano eastward to the coast.



Lowering of sector (a) 1106 ft. and sector (b) 603 ft.
Relief of sector (a) average of 1, 2, 3 and 4 = 1750 ft.
Average maximum slope gradient of sector (a) from 1, 2, 3 and 4 on topographic map = 1:0·89

Fig. 4. Cross section of the 3200 foot concentric sector of the eastern flank of the volcano showing the present and original surface.

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 2

Terrain parameters, amount of land lowering, and rate of denudation of various sections drawn parallel to the generalized contours of the topographic map of the Hydrographers volcano

Section parallel with generalized contours at given height (feet)	Amount of lowering (feet)		Average denudation rate feet/100 yr	cm/1000 yr	Present relief feet	m	Average maximum slope as gradient	Calculated average slope length feet	m
200	172	(52)	0.26	(7.9)	203	(62)	1:2.3	439	(133)
300	280	(85)	0.37	(11.3)	226	(69)	1:3.1	743	(226)
400	390	(119)	0.60	(18.3)	388	(118)	1:2.1	911	(277)
500	435	(132)	0.66	(20.1)	401	(122)	1:2.3	1006	(306)
600	422	(128)	0.65	(19.8)	438	(133)	1:2.9	1331	(405)
700	436	(133)	0.66	(20.1)	490	(149)	1:2.0	1096	(333)
800	420	(128)	0.65	(19.8)	700	(213)	1:2.2	1009	(307)
1000	565	(172)	0.87	(26.5)	725	(220)	1:1.7	1446	(440)
1200	554	(168)	0.85	(25.9)	813	(247)	1:1.75	1639	(498)
1400	731	(222)	1.12	(34.1)	1050	(319)	1:1.5	1919	(583)
1600	745	(226)	1.14	(34.7)	888	(270)	1:1.3	1449	(440)
1700	944	(287)	1.45	(44.2)	1035	(315)	1:1.0	1539	(468)
1800	847	(257)	1.30	(39.6)	1035	(315)	1:1.15	1577	(479)
2000	930	(283)	1.43	(43.6)	1313	(399)	1:1.1	1928	(586)
2200	996	(303)	1.53	(46.6)	1565	(476)	1:0.96	2169	(659)
2400	968	(294)	1.49	(45.4)	1525	(464)	1:0.83	1982	(603)
2600	973	(296)	1.50	(45.7)	1750	(532)	1:1.15	2667	(811)
2800	1002	(305)	1.54	(46.9)	1737	(528)	1:0.89	2325	(707)
3000	1106	(336)	1.70	(51.8)	1730	(526)	1:0.96	2398	(729)
3100	1083	(329)	1.67	(50.9)	1763	(536)	1:1.0	2493	(758)
3200	1106	(336)	1.70	(51.8)	1750	(532)	1:0.89	2342	(712)
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.

val of two thirds the relief. In most instances twelve or more readings were averaged.

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 sealevel 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 cliffed by marine erosion, and several benched levels 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 Managalase 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

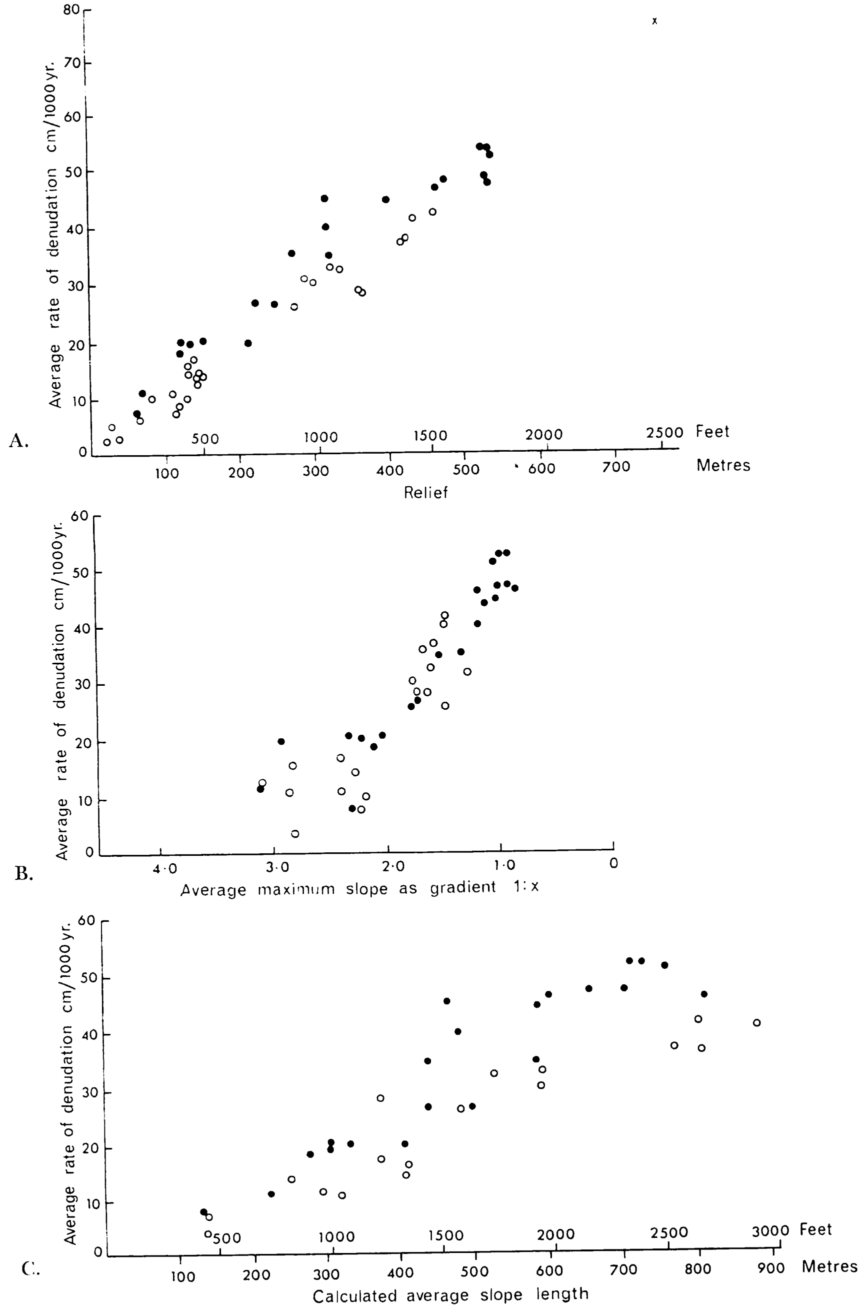


Fig. 5. Average rates of denudation plotted against (A) relief, (B) average maximum slope, and (C) average slope length. Data from the more dissected sectors is shown as closed circles, that from less dissected sectors is shown as open circles, and the cross at the top right hand corner in (A) is the datum from a rough estimate of the maximum amount of lowering in the volcanic center.

estimate of 60 centimeters per 1000 years for the Mamberamo River in 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, Glymph, 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 650,000 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 650,000 years.

The linear relationship between the calculated denudation rates and the present local relief and the compatability of the results with those of similar humid tropical areas suggest that the calculated denudation rates probably bear a simple relationship to present denudation rates. Schumm (1963) 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 (1963, 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 erosionally graded type (Ruxton, 1967) with straight slopes generally averaging about 37°, and this slope gradient seems to be independent of 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 gradients decline to as little as 18° except where oversteepened by marine erosion, and denudation rates are minimal.

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APPENDIX

Localities and descriptions of rock samples dated by the potassium-argon method. The laboratory numbers of the samples in the Australian National University collection are given in parentheses.

1. (GA 1544): Trachyandesite of Uoivi Volcanics. 9°8′ S, 148°27′ E. From south side of lava dome southwest of Uoivi at about 780 meters (2550 feet) altitude. Phenocrysts (8 percent) of augite and subordinate oxyhornblende, oxybiotite, and hypersthene, and xenocrysts (2 percent) of plagioclase and quartz, in a very fine grained groundmass of plagioclase, pyroxene, iron ore, minor biotite, and interstitial alkali feldspar (Ruxton, 1966b, analysis 36, table 2). The rock is fresh.

2. (GA 1545): Alkali basalt of Uoivi Volcanics, 9°8′ S, 148°26′ E. From massive lava flow half way down explosion crater on south side of lava cone near Kawowoki at about 730 meters (2400 feet) altitude. Phenocrysts and microphenocrysts of olivine and plagioclase occur in a fine grained ground mass of clinopyroxene, plagioclase, olivine, iron oxide, and very minor interstitial pale brown glass. Except for extensive replacement of olivine by iddingsite the rock is fresh.

3. (GA 1133): Trachybasalt of Uoivi Volcanics. 9°14′ S, 148°29′ E. From sill in Sesara Volcanics west of Gewoia at about 280 meters (920 feet) altitude. Phenocrysts (25 percent) of augite and olivine, and xenocrysts (1 percent) of quartz in a holocrystalline fine grained groundmass of plagioclase, clinopyroxene, minor olivine, and iron oxide, and interstitial alkali feldspar (Ruxton, 1966b, analysis 15, table 2). The pyroxene is slightly altered.

4. (GA 1134): Trachybasalt of Uoivi Volcanics. 9°16′ S, 148°31′ E. From sill in Sesara Volcanics south of Kinjaki at about 215 meters (700 feet) altitude. Phenocrysts and microphenocrysts (10 percent) of olivine and subordinate augite in a fine grained groundmass of plagioclase, pyroxene, iron oxide, and interstitial poorly crystallized, slightly turbid material (probably alkali feldspar and glass) which may not have retained all its radiogenic argon (Ruxton, 1966b, analysis 6, table 2).

5. (GA 1492): Latite of Hydrographers Volcanics. 9°13′ S, 148°25′ E. From thick massive lava flow on the scarp above the Bariji River at about 550 meters (1800 feet) altitude. Microphenocrysts (25 percent) of augite and olivine occur in a medium grained groundmass of plagioclase, alkali feldspar, iron ore, and minor biotite and interstitial altered material which is probably devitrified glass. This rock is inferior for dating purposes.

6. (GA 1488): Doreitic basalt of Hydrographers Volcanics. 9°00′ S, 148°23′ E. From thick massive lava flow exposed near major ridge crest of Hydrographers Range northwest of Numba at about 1158 meters (3800 feet) altitude. Petrographically very similar to specimen 9 but with much more olivine in the phenocrysts which make up about 40 percent of the rock (Ruxton, 1966b, analysis 14, table 2). The rock is fresh.

7. (GA 1490): Basaltic doreite of Hydrographers Volcanics. 9°00′ S, 148°22′ E. From massive lava flow exposed near crest of major ridge of Hydrographers Range northwest of Numba at about 1610 meters (5280 feet) altitude. Petrographically very

similar to specimen 6 but with only 25 percent of phenocrysts (Ruxton, 1966b, analysis 11, table 2). The rock is fresh.

8. (GA 1489): Doreite of Hydrographers Volcanics. 9°00′ S, 148°22′ E. From massive lava flow exposed near crest of major ridge of Hydrographers Range northwest of Numba at about 1830 meters (6000 feet) altitude. Petrographically very similar to specimen 6 but without olivine in the phenocrysts. The rock is fresh.

9. (GA 1487): Dacitic doreite of Hydrographers Volcanics. 9°00′ S, 148°23′ E. From thick massive lava flow exposed on subordinate ridge of Hydrographers Range northwest of Numba at about 1050 meters (3500 feet) altitude. Phenocrysts (50 percent) of complexly zoned and twinned plagioclase, augite, hypersthene, olivine, and minor brown hornblende, in a fine grained to cryptocrystalline groundmass mainly of feldspar with minor pyroxene and iron oxide, very minor biotite, and some interstitial glass (Ruxton, 1966b, analysis 24, table 2). The rock is fresh.

10. (GA 1132): Latite of Hydrographers Volcanics. 9°00′ S, 148°29′ E. From boulder in agglomerate bed in creek section on eastern flanks of Hydrographers Range at about 185 meters (600 feet) altitude. Phenocrysts and microphenocrysts (40 percent) of complexly zoned and twinned plagioclase and subordinate augite, hypersthene, brown hornblende and biotite occur in a cryptocrystalline groundmass of probably plagioclase, pyroxene, and glass. The glass is partly devitrified.

11. (GA 1483): Latite basalt of Sesara Volcanics. 9°15′ S, 148°28′ E. From massive lava flow near crest of major ridge west of Biriri at about 670 meters (2200 feet) altitude. Phenocrysts and microphenocrysts (35 percent) of augite and olivine in a fine grained groundmass of plagioclase, clinopyroxene, iron oxide, minor biotite, and interstitial alkali feldspar. (Ruxton, 1966b, analysis 9, table 2). Apart from some alteration of olivine to iddingsite the rock is fresh.

12. (GA 1484): Leucite basalt of Sesara Volcanics. 9°14′ S, 148°28′ E. From flow-brecciated lava in Bariji gorge at about 235 meters (770 feet) altitude. Phenocrysts and microphenocrysts of olivine occur in a cryptocrystalline groundmass of probably feldspar, nepheline, pseudoleucite, pyroxene, and olivine. This rock is altered and is inferior for dating purposes.

13. (GA 1485): Leucite basalt of Sesara Volcanics. 9°15′ S, 148°30′ E. From massive lava flow east of Manana at about 150 meters (500 feet) altitude. Phenocrysts (45 percent) of zoned augite and minor olivine occur in a fine grained somewhat altered groundmass of feldspar, nepheline, iron oxide, biotite, and very minor pseudoleucite (Ruxton, 1966b, analysis 5, table 2).

14. (GA 1486): Latitic picrite of Sesara Volcanics. 9°14′ S, 148°29′ E. From columnar jointed lava of volcanic neck at about 180 meters (600 feet) altitude. Phenocrysts (50 percent) of co-dominant olivine and augite in a fine grained groundmass of mainly plagioclase with minor clinopyroxene, olivine, and iron oxide (Ruxton, 1966b, analysis 2, table 2). This rock is fresh.