70-9969

ATKINSON, Ian Athol Edward, 1932-
RATES OF ECOSYSTEM DEVELOPMENT ON
SOME HAWAIIAN LAVA FLOWS.

University of Hawaii, Ph.D., 1969
Agriculture, soil science

University Microfilms, Inc., Ann Arbor, Michigan

RATES OF ECOSYSTEM DEVELOPMENT
ON SOME HAWAIIAN LAVA FLOWS

A DISSERTATION SUBMITTED TO THE
GRADUATE DIVISION OF THE UNIVERSITY OF HAWAII
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

SOIL SCIENCE

AUGUST 1969

By

Ian Athol Edward Atkinson

DISSERTATION COMMITTEE:

L.D. Swindale, Chairman

G. Donald Sherman

G. Uehara

Y.N. Tamimi

C.H. Lamoureux

ACKNOWLEDGEMENTS

Many people have helped me in various ways during the course of this work. In particular, I am especially grateful to the following students and faculty at the University of Hawaii:

Dr. R.H. Jones, Information Science Dept., for his helpful advice concerning the use and interpretation of multiple regression analyses.

Mr. C.L. Schroth, Agronomy and Soil Science Dept., for general discussion of many aspects of the problem, particular assistance during the running of the computer programs, and for collecting the samples of Samoan lavas used in this study.

Mr. D.L. Taylor, Chemistry Dept., for his careful instruction and help in the use of X-ray fluorescence techniques.

Mrs. Annie Chang, Agronomy and Soil Science Dept., and Mr. R.H. Suehisa, Plant Physiology Dept., for their advice concerning technique with the calcium analyses.

Miss Bernadette M. Paik, Agronomy and Soil Science Dept., for carrying out the C.E.C. determinations.

Dr. S.A. El-Swaify, Agronomy and Soil Science Dept., for helpful discussion of many aspects of pH measurements.

Dr. H. Ikawa, Agronomy and Soil Science Dept., for introducing me to the solution technique of Suhr and Ingamells (1966).

Dr. G.A. Macdonald, Geoscience Dept., for answering many questions of a geological nature.

Dr. F.B. Thompson, Superintendent of the University Branch Station at Hilo for his assistance in arranging transport during all phases of the field work.

Mr. Humphrey Ezumah, Agronomy and Soil Science Dept., for his assistance with grinding the earliest batch of rock samples.

Mr. Renye Matsumura, Waiakea Experimental Farm, for accompanying me on one of the more difficult field trips.

Dr. S. Pandey, Agronomy and Soil Science Dept., for patient advice concerning thesis reproduction.

Mrs. Susan L. Aiu and Mr. R. Miura, Instructional Resources Center, for final drafting and photographing of the diagrams.

Mrs. H.L. Ramage for her continuing patience and attention to detail in typing the final copy of the dissertation.

My wife, Pamela, for her critical and constructive reading of the manuscript, many hours of typing during preparation of the first draft, and for carrying out all stages of photographic production.

The work reported in this thesis was funded through Project 140 F: "Soils in introduced and indigenous forests", a Hawaii Agricultural Experiment Station project.

My period of study in Hawaii was made possible through the financial support of a National Research Fellowship awarded by the New Zealand Government.

ABSTRACT

The objective of this study was to measure rates of plant succession and rock weathering during the first 400 years of ecosystem development on Hawaiian basalt lava flows. The flows chosen for study were on the wettest slopes of Mauna Loa and Kilauea in a rainfall of 90 to 250 inches and between elevations of 40 to 4000 feet. These flows are largely free from ash.

The oldest dated flow on Hawaii occurred little more than 200 years ago (1750 A.D.), which gives insufficient time for much development. To measure rates over a longer period, e.g. 400 years, it was necessary to date older flows. Since obtaining carbon for C-14 dating of the older flows was unlikely, a major part of the study was concerned with searching for a method of aging late prehistoric flows.

The vegetation of nine aa and two pahoehoe flows was examined and samples obtained of unweathered and weathered rocks. Of the methods investigated, compositional changes between unweathered and weathered rocks showed most promise as age indices; in particular, pH change, sodium loss, calcium loss, titanium gain, and a 110-350°C. weight loss measuring adsorbed and hydrated water. These measurements from 5 dated aa flows were used as dependent variables in a regression analysis. Included as independent variables were age, climate, effective plants (biotic factor), rock composition, rock texture and porosity. Two of the regression equations obtained were solved inversely to give an estimation of age with confidence limits of ± 87 and ± 108 years. These equations, when used to age two prehistoric aa flows, gave ages that agreed within 25 years (c. 360 years B.P.). The two equations used different compositional parameters, viz. pH, sodium and calcium loss in one case, and the 110-350°C. weight loss in the other. Thus, although no other dates are available for comparison with these ages, the agreement in the results indicates that these methods are worthy of further study.

Four trends in plant succession, all beginning on bare aa lava, were recognized from the observations of vegetation in this high-rainfall region. A coastal succession appears to culminate in Pandanus forest. At altitudes below 1000 feet, successional trends are towards Metrosideros or Metrosideros/Diospyros forests. The latter trend appears to be associated with areas where rainfall is less than 100 inches and where there is a tendency towards summer-dry periods. At higher altitudes (3000 to 4000 feet), a relatively stable stage commonly reached is that of Metrosideros/Cibotium forest.

Concerning rates of plant succession, it was concluded that in the humid region with annual temperature of about 70°F., forest ($>80\%$ cover of trees) can develop on aa flows within 200 years of flow formation. At higher altitudes (3000 - 4000 feet with annual temperatures of c. 60°F.), forest is developed within 300 years. These rates are slower than those reported elsewhere in the tropics but may be typical of succession rates on aa lava that has little ash.

Considering rates of rock weathering, the following mean rates of change over the 400 year period studied were found: pH changes of 0.76 - 1.50 pH units per century; sodium loss of $<0.1 - 0.3\%$ per century; calcium loss of $<0.1 - 0.4\%$ per century; relative titanium gain of 0.05 - 0.18% per century; and gain in water of 0.6 - 0.9% per century. There was a clear indication that rates of weathering were decreasing with time.

In this high-rainfall region, the rate of succession was highest at altitudes below 1000 feet. However, the rate of weathering on these flows was greater between 3000 and 4000 feet. It was concluded that temperature, with its effects on plant growth, evaporation and accumulation of organic matter, was the differentiating factor.

TABLE OF CONTENTS

TABLES OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

INTRODUCTION

The slopes of Mauna Loa and Kilauea on the Island of Hawaii provide an array of lava flows of differing age in a variety of climates. Perhaps there is as fine an opportunity here as anywhere in the tropics to study trends and rates of change within lava-flow ecosystems. Although some information is available on the earliest stages of succession, especially in areas of lower rainfall, there is little recorded about the wetter regions with rainfall exceeding 100 inches. This is particularly the case when rates of change in soil and vegetation properties are considered. Thus the first objective of this study was to determine the trends of development occurring in this region of higher rainfall and see if any generalizations concerning rates of change were possible. Attention was focussed on two ecosystem processes; weathering and plant succession.

Measurements of rates of change are not possible without sampling sites of known age. The oldest dated lava flow on Hawaii was erupted from Kilauea about 1750 A.D. This date gives a time span from the present of little more than 200 years, a very short period in the development of a lava-flow ecosystem. No carbon-dates are available for older flows and it is not easy to find suitable material for C-14 dating. For this reason it became important to find some way of extending the 200 year time span, at least by a few hundred years. Without an adequate time-scale it is difficult to follow trends or to measure rates of change. Thus the major part of this study is concerned with exploring methods of aging lava-flow ecosystems using measurements of the vegetation or weathering rock.

A second objective of the study was to determine the relative importance of factors that influence a lava-flow ecosystem during the early stages of its development, particularly climate, physical and chemical composition of the parent material, biota and the age of the system. The general importance of these factors in influencing soil and vegetation development is well established, but what are their relative effects during early stages of weathering and succession? In the final part of this study, it was found possible to combine data from the historic flows with that from two prehistoric flows and reach preliminary conclusions concerning this question.

REVIEW OF LITERATURE

Methods of Aging Lava-Flow Ecosystems

In geologically young lava flows the age of the rock and that of the ecosystem developed from its surface are identical, except where there has been major disturbance such as slips, fire, or more lava. Methods of aging rocks that might be suitable for dating ecosystems are included in this review.

Radioactive Isotope Methods

Many rocks have been aged using isotopic ratios such as the decay pairs of potassium-argon, rubidium-strontium, thorium-lead and uranium-lead. The time-scale for these methods spans millions of years and concentrations of these isotopes are usually too low for dating rocks in the range 0 - 10,000 years B.P. The ionium method can be applied to the time span from the present to about 300,000 years B.P. but it requires a chronologically undisturbed sediment column (Volchok and Kulp 1957), and is therefore unsuitable for solid rock.

At present the isotopic method with the greatest potential is still the carbon-14 technique which can be used to cover the range 200 to 60,000 years B.P. Its disadvantage in this case is the difficulty of finding carbonaceous material in or beneath the lava flow under investigation. There are numerous prehistoric flows in the study area but only two C-14 dates are available, one of <400 years for charcoal from a flow in the Puna district and the other of approximately 2000 years based on two charcoal samples collected in cinders at Waiakea (Macdonald and Eaton 1964).

The carbon-14 method has been used also to determine minimum ages for the humic B horizons of podzols (Perrin et al 1964) and to age humus fractions of chernozem soils (Campbell et al 1967). In the present study, a C-14 age for any humus fraction would only be an average age and would not measure the absolute age of the ecosystem.

Thermoluminescence

Sabels (1963) developed a technique of aging basalt lava flows using natural alpha activity and thermoluminescence induced by X-rays. He obtained good agreement with field evidence on northern Arizona basaltic lavas in the time range of 900 to 35,000 years B.P. Sabels concluded that the method was applicable to volcanic fields in which a large number of lava samples could be collected from flows of different age but similar composition. Although thermoluminescence techniques have been applied to the aging of limestones and ancient pottery, apparently no further work has been published on the aging of lava flows.

Palaeomagnetism

R. L. Dubois has developed a method of archeomagnetic dating based on the fact that magnetic iron oxides in clays, when heated to 1,100° F, orientate with the earth's magnetic field (Weaver 1967). By measuring this orientation and relating it to a map of polar wanderings, an age can be given for the time when the clay was heated.

It may be possible to apply this principle to soils that have been covered and baked by young lavas, or alternatively measure the orientation of the magnetic minerals in the lava itself. Doell and Cox (1961) studied palaeomagnetism in Hawaiian lava flows and found that directions of magnetization were varying more slowly in Hawaii than other parts of the world. No attempt was made to develop this approach in the present study since the time span required is large and more palaeomagnetic information is needed.

Fission Track Method

Several methods of dating using radiation damage have been investigated and of these the fission track method of Price and Walker (1963) covers the longest time-span. The method requires uranium contents in excess of 1 ppm so that some way of concentrating the uranium-containing zircons (which are usually rare in basalt) would be needed before this technique could be applied to a basalt flow.

Hydration Rind Method

Friedman (1968) aged rhyolite flows by measuring the thickness of the hydration rind developed at an exposed glass surface. Since volcanic glass sometimes occurs in basaltic rock, a search for such hydration rinds was made (p. 99).

Ecosystem Parameters

The soil, plants and animals of any particular part of the landscape are continuously interacting through processes of accumulation, transfer and loss of matter and energy. This interlocking but open system of living and non-living components showing some degree of stability is conveniently termed an ecosystem and may be of any size depending on what is most useful to the aims of the particular study.

From the point of view of age determination, we may divide a lava-flow ecosystem into five components: atmosphere, animals, plants (vegetation), soil, and weathering parent material. Of these, vegetation, soil and parent material change most slowly and some of their properties may be suitable as indices of age.

Vegetation Parameters: The most frequently used aging method in ecosystem studies is that of dating a surface from ring counts of the trees growing on it, e.g. Lawrence (1950), Dickson and Crocker (1953), Olson (1958). Sometimes new volcanic surfaces have been aged by taking sections from nearby trees and observing the point in the ring sequence where ashfall has caused a narrow growth ring (Lawrence 1954, Druce 1966, Eggler 1967).

Growth rings are unreliable in most tropical trees and even when clearly defined they may not be formed until after the tree has reached a certain age (Richards 1952).

Density, cover and basal area all change with time although they have not been used as age parameters in published studies. Dickson and Crocker (1953) working on Mt. Shasta, California, found a curvilinear increase in shrub cover of land-slides between 60 and 566 years old. In Alaska, Viereck (1966) found a steadily increasing cover of mosses in a sequence of glacial outwash surfaces up to 300 years old. Many vegetation variables increase or decrease with time but at varying rates, thus preventing their use as age indices.

A lichenometric dating method has been developed by Beschel (1961) in which diameter growth of the largest lichens is related to time. For example, Stork's (1963) data from Northern Sweden shows an almost linear relationship between lichen growth and time for the 200 year period studied. Although this method is not suitable for forested lava flows, it may have application to the sparsely vegetated flows of the drier parts of Mauna Loa.

The disadvantage of relying on a vegetation parameter to age lava-flow ecosystems is that disturbance or destruction of the vegetation often removes or complicates the evidence of age.

Soil Parameters: The upper soil horizon on the older forested flows of Mauna Loa and Kilauea consists almost entirely of organic matter with the rocky horizon beneath. Possibly some property of this organic horizon could be used as an age index. Kosaka (1963) recognized stages of humification in which there are decreasing amounts of methoxyl-carbon with increasing humification. If methoxyl-carbon was used as an age index, corrections would be needed for recent additions of methoxyl-C from the vegetation. The average age measured would then approach the age of the oldest methoxyl carbon more closely.

Many soil parameters change with time but often they are not single-valued functions of time. Thus the studies of Crocker and Major (1955) and Crocker and Dickson (1957) show that total organic carbon and total nitrogen, first increase with time and then decrease. Other parameters show uniform trends at least for a portion of the time-scale studied, e.g. decrease of carbonates in sand-dune ecosystems (Salisbury 1925, Olson 1958) and decrease in pH accompanying podzol development (Chandler 1942). Burges and Drover (1953), studying podzol development on sand, found an increase in the depth and thickness of the B horizon with increasing age.

Van Wambeke (1962) discusses criteria for classifying tropical soils by relative age and lists soil structure, silt-clay ratios and percentage of weatherable minerals as important. These parameters may have application to fully developed soils but would not be useful in the young soils of the present study where the amount of clay is very small and the amount of weatherable material very large.

There are two main disadvantages of using a soil parameter to age a lava-flow ecosystem. Many soil properties are resultants of both losses and gains to the system so that total losses or gains cannot be measured. This is particularly important where addition of volcanic ash is a possibility. Although no evidence of ash was found in profiles examined on the lava-flows studied, ash additions cannot be ruled out. Wentworth (1938) records that during the 1852 eruption on the eastern slope of Mauna Loa, ash fell thickly on the roofs of houses in Hilo, 25 miles away. In the 1868 eruption of Mauna Loa, showers of ash and pumice were ejected distances of 10 to 15 miles in all directions.

The second disadvantage of soil parameters is that often they reflect equilibrium conditions dependent on the local soil environment rather than time. An example of this is the dependence of gibbsite formation on pH and silicate ion concentration (Swindale and Uehara 1966). With no change in the soil environment, the amount of gibbsite formed is time-dependent. However, with a change in pH, such as might occur with establishment of a new plant in the succession, a new equilibrium would develop in which the amount of gibbsite present might, temporarily at least, be less than the amount present at an earlier stage of development.

<u>Weathered Rock Parameters:</u> If changes in a particular parameter of the weathering rock can be related to time using lava flows of known age, it may be possible to use this relationship to estimate the ages of prehistoric flows. Ideally a linear or at least a mathematically predictable change of the parameter with time is required.

Chemical processes of weathering are dominant in the tropical climate of Hawaii, but both physical and chemical changes are closely associated as weathering proceeds. The principal chemical processes are hydration and hydrolysis, oxidation and solution. Each of these processes affects many rock properties, some of which may be useful age parameters.

Hydration, or adsorption of water molecules, followed by hydrolysis in which H ions replace metallic cations in primary minerals, are the first steps in weathering. In their study of diorite weathering in Antartica, Kelly and Zumberge (1961) measured a 1.23% increase in uncombined water between fresh and weathered rock. Thus a direct measure of change in the state of hydration may be suitable as an age parameter. Volume increase and associated decrease in particle density resulting from hydration changes can be expected to change many physical properties which may provide further possibilities for age indices.

The main oxidation change is that of ferrous ion changing to the ferric state, although manganous ion (Mn^{2+}) to manganic (Mn^{4+}) and sulfide-sulfate oxidation can also be expected. Kelly and Zumberge (1961) found that oxidation of ferrous ion in pyrrhotite and biotite to ferric ion in limonite was the principal change taking place in the early stages of weathering they studied. Redox measurements would reflect change in the ferrous-ferric ion ratio and determination of the magnetite-maghemite ratio would also indicate change in the oxidation state of iron. Like hydration, oxidation is an early weathering change and therefore could be a sensitive indicator of age for the time span under study.

Decomposition of silicate crystals by incongruent solution results in many mineralogical and elemental changes. In her study of the weathering of basic igneous rocks, Smith (1962) found the following sequence of increasing mineral stability: olivine, labradorite, augite, magnetite, ilmenite and hematite, although the latter is both a primary mineral and a secondary weathering product. Bates (1960) places olivine, felspars and monoclinic pyroxene of Hawaiian rocks in a similar order of stability.

The differential loss of elements from weathering rock, when expressed on a percentage basis, results in relative gains and losses. An indication of the trends to be expected in basic rocks can be obtained from the data of Harrison (1933) Polynov (1937), Goldich (1938), Tiller (1958), Wells (1960), Swindale (1966). Thus, Si, Ca, Mg, Na, and K are lost while Ti, Al and Fe concentrate with time. Although present in initially much smaller amounts, the elements Sr, Ba, and Zn are lost while Ga, Mo, Cr, and V tend to concentrate. The pattern of change for Mn, Ni, Co, Cu and Zr is not clear. Walker (1964) has shown how total P decreases with time accompanied by a narrowing of the inorganic P: organic P ratio.

Several of these elements are clearly worth measuring as potential age indices. Some will be present in amounts too small for changes to be measured in the 500 year time span under study; in other cases the rate of change may be too slow.

Some elemental ratios may be more suitable as age indices than changes in single elements. Ratios that have been used as weathering indices are summarized by Jenny (1941). These include silica:alumina, base:alumina, alkali:alumina, calcium:magnesium and potassium:sodium ratios.

In the present study it was decided to concentrate attention on parameters of the vegetation and the weathered rock. The possibilities for age indices were listed in order of likelihood. Among the weathered rock parameters, attention was given initially to elemental changes, particularly strontium and titanium, and to hydration changes. As the search continued and more information became available, the order of possibilities was continually altered, so that the age index which seemed to have the greatest potential was kept as the focus of interest.

Trends and Rates of Ecosystem Development

A grouping of ecosystem processes is necessary before discussing rates of development. For the purpose of this study six main groups of processes are distinguished:

(i) plant succession: compositional change in the vegetation resulting from replacement of one species by another.

(ii) stratification or layering: structural change in the vegetation resulting from plant growth.

(iii) weathering: compositional change in the parent material.

(iv) biocycling: plant and animal uptake of minerals released by weathering and their return to the soil in combination with carbonaceous and nitrogenous material.

(v) translocation/horizonation processes: redistribution and loss by leaching and eluviation of both weathering products and organic material; processes that are associated with the development of soil horizons.

(vi) erosion/deposition processes: affect both vegetation and soil.

Although many studies of tropical vegetation and soils have been published it is seldom that vegetation and soil studies are integrated. A notable exception is the study of Morison et al. (1948) who, in their analysis of tropical soil-vegetation catenas in Africa, stressed the importance of topography in determining the type of soil-vegetation system that developed. Studies of rates of change in tropical ecosystems appear to be lacking.

The earliest studies of plant succession on lava flows in Hawaii appear to be those of Forbes (1912) and MacCaughey (1917). Further contributions have been made by Robyns and Lamb (1939), Skottsberg (1941), Doty (1956, 1961), Doty and Mueller-Dombois (1966) and Smathers (1966). The trends of succession in the early stages are reasonably well understood but no measurements of succession rates under differing climatic conditions have been made.

Elsewhere in the tropics, the best documented case of forest development on a recent volcanic surface is that of Krakatau Island (Richards 1952). Here, in a rainfall of more than 100 inches, a large part of the surface bared by the 1884 eruption was covered by closed forest within 45 years. Though made in a warm temperate climate rather than a tropical one, the study of the vegetation of Sakurajima, Japan by Tagawa (1964) is notable for its attention to rates of development. A scrub stage was reached within 100 years and forest within 150 years.

One of the earliest studies of weathering in Hawaii is that of McGeorge (1917) who compared the composition of fresh basaltic boulders with that of their weathered shells. These shells are considerably more weathered than the weathered rocks analysed in this study but McGeorge's results indicate the trends to be expected: losses of silicon, ferrous ion, calcium, sodium and manganese; relative gains of aluminum, ferric ion, titanium and an absolute gain of water.

Most studies dealing with soil changes in the tropics have paid attention to elemental changes during weathering and clay formation. An exception is that of Jenny, Gessel and Bingham (1949) who compare decomposition rates of organic matter between tropical and temperate soils. Barton (1916) studied the weathering of granite in two very dry parts of Egypt, Aswan and Gizeh. He found an average rate of disintegration and exfoliation of 0.1 to 0.5 cm in 1000 years. Polynov's (1937) study was a major contribution towards understanding the relative mobilities of elements lost during weathering and he concluded that even in a moist tropical climate the conversion of rock to clay would require "a very considerable time, measurable only on the geological scale".

Sherman and Ikawa (1968) discuss factors influencing the rate of weathering and soil formation in the Hawaiian Islands. They distinguish intensity factors of environment and time from capacity factors which determine the resistance of a mineral to weathering. Environmental intensity factors include temperature, rainfall, drainage and vegetation while capacity factors include rock texture, stability of minerals to decomposition and the nature of the mineral surface or coating.

The weathering of olivine basalt was examined by Sherman and Uehara (1956) who concluded that the direction of weathering was very dependent on the rate of removal of bases. Uehara, Ikawa and Sherman (1966), studied the desilication of halloysite, concluding that the rate of this weathering process is a function of the amount of water passing through unit volume of the material. In general agreement with this is the conclusion of Ruxton (1968) whose study of andesitic ash soils in Papua suggests that the rate of weathering is limited by rainfall and is not primarily determined by temperature.

Examples of ecosystem studies where soil and vegetation changes are correlated appear to be restricted to temperate or cold environments. In perhaps the earliest study of this type, Salisbury (1925) working with a dune sequence measured a mean annual percentage loss of calcium carbonate varying between 0.6 and 0.8% per year over a period of about 250 years. Olson (1958) also working with a dune sequence found that the loss of free carbonate could be fitted to a negative exponential function over a period of 600 years. Dickson and Crocker (1953) in their pioneering study of ecosystem development on a series of landslides in California, measured changes in tree density, basal area, shrub cover, ground cover, and correlated these with changes in pH, organic carbon, total nitrogen, and grain numbers of plagioclases and volcanic glasses. Crocker and Major (1955), in a similar type of study on glacial outwash surfaces in Alaska, point out how the rate of change in soil properties is very dependent on the micro-pattern of plant colonization, this itself being influenced by chance factors of dispersal. Tezuka's (1961) study of ecosystem development in Japan is one of the few such studies made in a volcanic environment. He used changes in humus content (ignition loss) as his measure of time.

In the present study, attention was directed firstly towards elucidating trends of succession and weathering in the earliest stages of ecosystem development on lava-flows. Secondly, it was aimed to measure the rates of these processes and as far as possible to establish the relative importance of each of the factors affecting these rates of change.

DESCRIPTION OF STUDY AREA

The lava flows studied are on the volcanoes of Mauna Loa (13,018') and Kilauea (4,090') on the Island of Hawaii lying between latitude 19° 20' - 19° 45' and longitude 154° 50' - 155° 20'. The study area (Fig. 1) includes:

(i) the eastern slopes of Mauna Loa that lie west and south of Hilo and extend from sea-level to 4,000 feet.

(ii) the northern and south-eastern slopes of the Puna rift zone of Kilauea within 9 miles of Pahoa and extending from sea-level to 1,000 feet.

Climate

Mean annual temperatures vary from 73.1° near sea-level (Hilo Airport) to about 59° F. at 4,000 feet (based on a temperature lapse rate of 3.5° F. per thousand feet recommended by Mr. Saul Price, U.S. Weather Bureau, pers. comm.) Mean summer and mean winter temperatures are 74.8 and 71.4° F. near sea-level and approximately 61.5 and 59.5° F. at 4,000 feet. The mean variation between warmest (August) and coldest (February) months is between 5 and 6° F. and probably never exceeds 9° F. (Blumenstock and Price 1967). The area is frost-free.

Mean annual rainfall varies from about 80 inches in the coastal Puna district to over 200 inches at 2,000 feet on Mauna Loa. Above this elevation rainfall decreases to around 125 inches at 4,000 feet (Fig. 2a). Below 1,000 feet, rainfall is rather unevenly distributed with the wettest month (December or March), often receiving more than twice the rainfall of the driest month, June (Fig. 2b). At higher altitudes, and particularly above 2000 feet, monthly rainfall distribution is fairly uniform. Annual rainfall throughout the area is highly variable. In areas where monthly averages are all above 10 inches, there may be occasional months with only 1 or 2 inches of rain (Blumenstock and Price, loc. cit.). Rainfall intensities in excess of 9 inches in 24 hours occur once every two or three years at most localities including those of high average rainfall.

The eastern slopes of Mauna Loa are exposed to the north-easterly trade winds which blow for more than 70% of the time, particularly from May to September. Orographic cloud is frequent, particularly over the Mauna Loa slopes above 1000 feet (Mordy 1957) and at most places the average relative humidity is between 70 and 80% (Blumenstock and Price, loc. cit.). Both widespread storms and intense local storms are infrequent.

Topography

Because of their youth, lava flows of the area are undissected. These lavas are highly permeable and without permanent streams. Surface water is restricted to small unfissured areas on some pahoehoe flows. Overall slopes are long and gentle averaging about 3 - 4° on Mauna Loa and 1 - 4° in the Puna rift region. Locally, the land surface is generally undulating except where broken by the more craggy surface of recent aa flows.

Geology

The surface lava flows of the study area are either late Pleistocene or Recent in age. Those of Mauna Loa belong to the Kau volcanic

Figure 1. Location of study area and position of sampling sites.

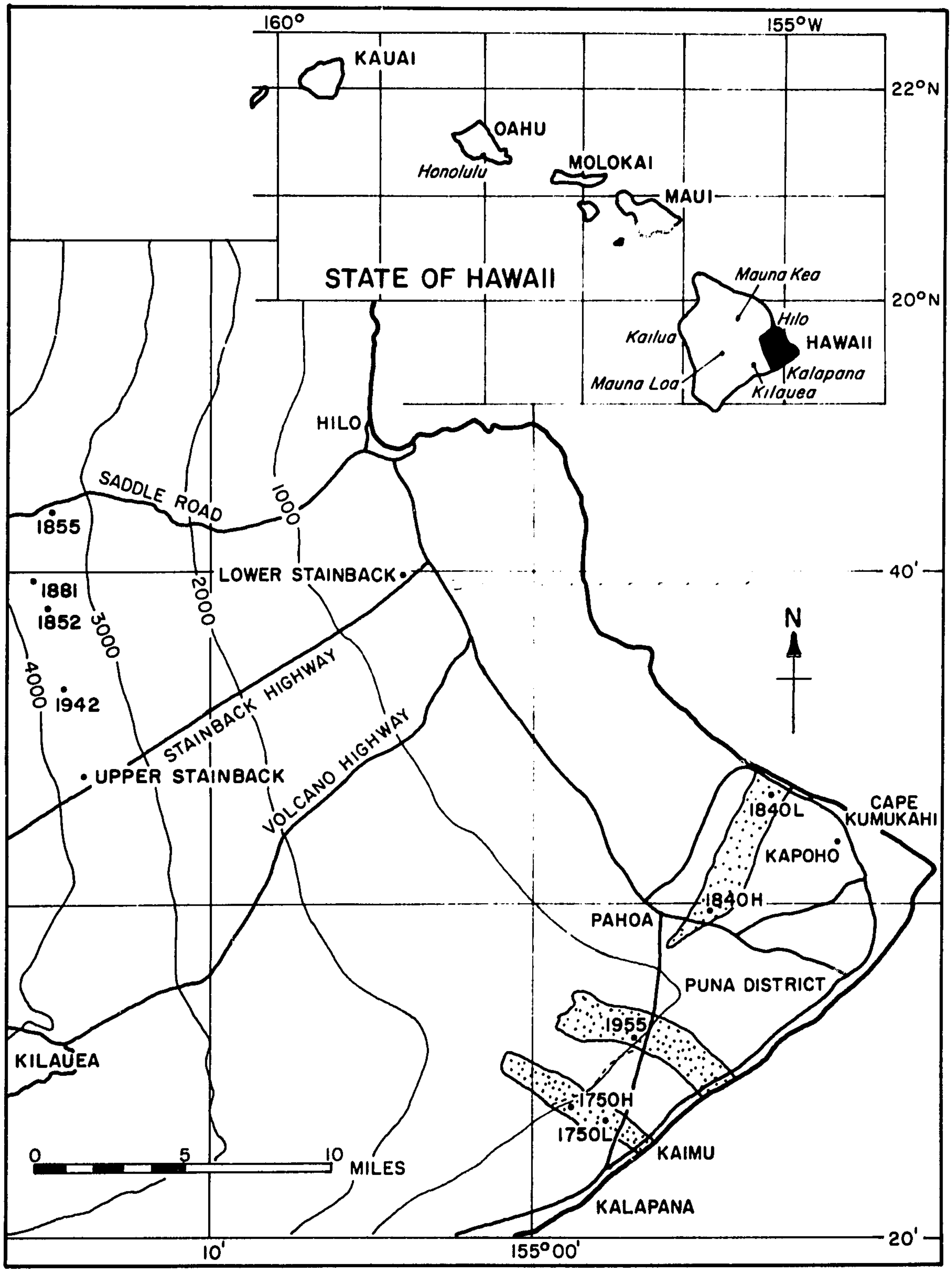
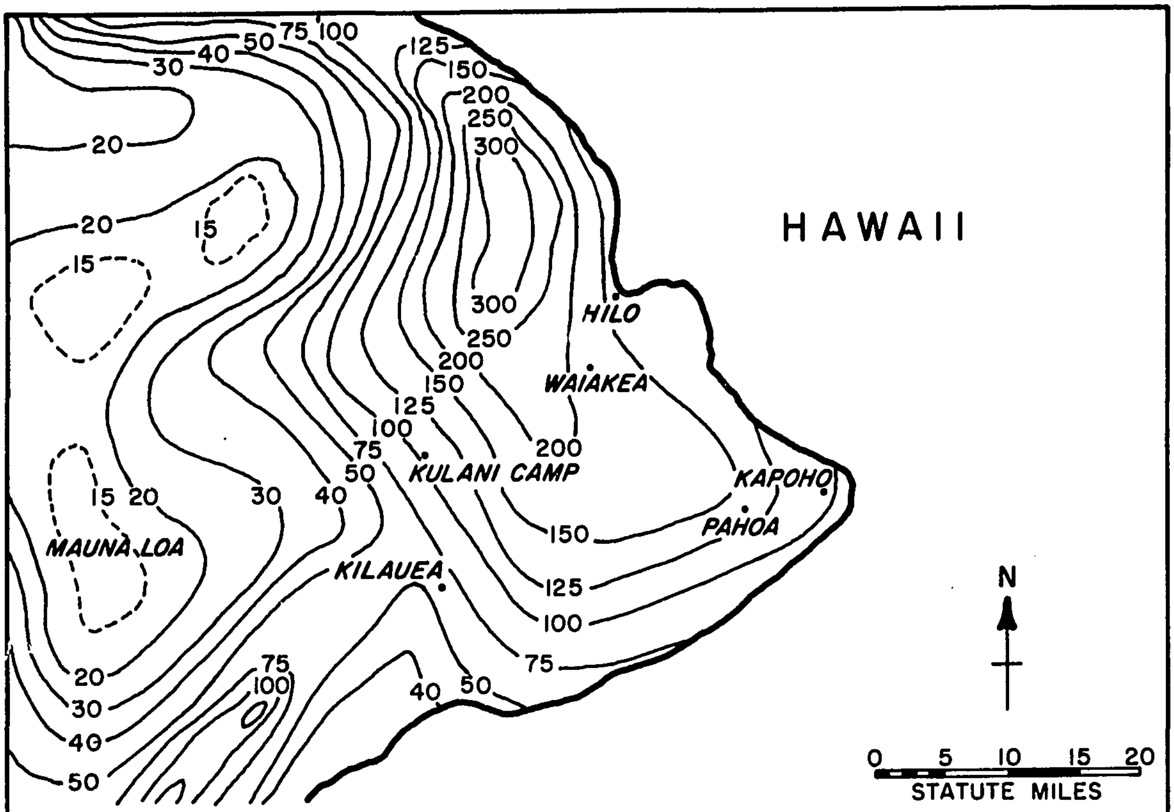
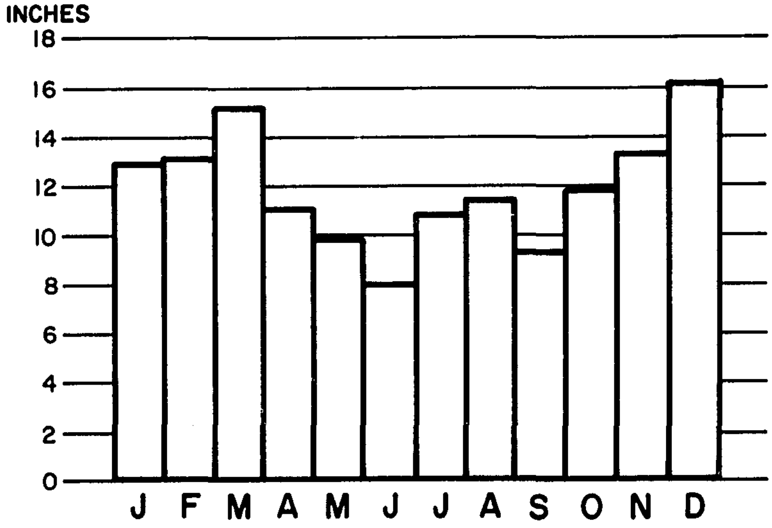

160°
155°W
22°N
20°N
KAUAI
OAHU
Honolulu
MOLOKAI
MAUI
STATE OF HAWAII
Mauna Kea
Hilo
HAWAII
Kailua
Mauna Loa
Kalapana
Kilauea
HILO
SADDLE ROAD
1000
1855
LOWER STAINBACK
1881
1852
2000
3000
4000
1942
STAINBACK HIGHWAY
UPPER STAINBACK
VOLCANO HIGHWAY
40'
N
CAPE KUMUKAHI
1840L
KAPOHO
1840H
PAHOA
PUNA DISTRICT
1955
KILAUEA
1750H
1750L
KAIMU
0
5
10
MILES
KALAPANA
20'
10'
155°00'

Figure 2. Rainfall in the study area.



2a. MEAN ANNUAL PRECIPITATION (in.). After Blumenstock and Price, 1967.



2b. MONTHLY RAINFALL AT PAHOA. After Blumenstock and Price, 1967.

series and those of Kilauea to the Puna series (Stearns and Macdonald 1946). Among the historic flows studied, the age of the 1750 (?) Kilauea flow is not known for certain. The only reference is that of Hitchcock (1911 p. 164) who gives the period 1730 to 1754 as the time of an eruption at Kaimu. The 1750 date used for this study follows that given on the geologic map of Hawaii (Stearns and Macdonald, loc. cit.).

Both volcanic series include pahoehoe and aa flows. These are generally 10 to 15 feet thick (Stearns 1966). Tubes and other cavities originating from collapse after cooling are numerous in the pahoehoe flows.

Numerous craters as well as cinder and spatter cones are aligned along the Puna rift but these are largely absent from the sector of Mauna Loa studied. Pumice deposits associated with cones and craters cover only small areas (Stearns and Macdonald, loc. cit.). Wentworth (1938) and Frazer (1960) record historic eruptions of Mauna Loa and Kilauea that spread ash or dust over wide areas of Hawaii so that small amounts of ash have certainly fallen on the later prehistoric and historic flows studied. Field observation of the organic horizon overlying these flows did not show any evidence of ash so that its contribution to the soils here is likely to be small. The Pahala ash, widespread in the south-eastern half of the island, is thought to have originated largely from phreatomagmatic explosions of Kilauea (Frazer 1960), and has been dated from charcoal as last glacial (Wisconsin) in age (Rubin and Berthold 1961). The only way in which Pahala ash could contribute to soil formation on young flows would be by redistribution by wind. This would require a drier climate than that of the study area.

All the lavas sampled belong to the tholeiitic suite as defined by Macdonald and Katsura (1962). These include olivine basalts (>5% modal olivine), basalts (<5% modal olivine) and oceanites (picrite basalts with very abundant phenocrysts of olivine and less than 30% felspar) (Macdonald and Katsura 1964). Macdonald (1949a) describes the olivine basalts and basalts as usually porphyritic in texture with a groundmass of 25 - 50% plagioclase (labradorite dominant), 25 - 50% monoclinic pyroxene, 1 - 15% olivine and 7 - 15% magnetite and ilmenite. Apatite is recognisable in a few specimens and some contain glass. The phenocrysts are largely olivine (up to 8mm long), plagioclase and augite (both up to 10mm long). Average chemical analyses of rocks from Kilauea and Mauna Loa are given in Table 1.

Soils

Cline (1955) mapped the soils of the later prehistoric and historic flows as lithosols while those on Pahala ash and older flows were mapped as hydrol humic latosols or humic latosols. The lithosols occupy by far the larger area and, apart from small surface accumulations of organic matter, they show little profile development.

In terms of the U.S. Comprehensive Classification the soils of the later prehistoric and historic flows are classified as entisols and lithic folists in the order of histosols (see Soil Survey Staff, 1968).

Vegetation

Forest dominated by Metrosideros (Metrosideros polymorpha) covers the greater part of the study area even though much of this has been replaced by settlements. This forest is classified by Krajina (1963) as mesophytic marine tropical and subtropical forest (zone D-O_1). A general description is given by Fosberg (1961). Figure 3 shows a simplified vegetation profile, typical of the northern and wettest part of the area. This diagram, based on surviving stands of vegetation, is an interpretation of the forest pattern as it was before disturbance by man and introduced animals. Pandanus (*Pandanus tectorius*) forest dominates the coastal fringe but this changes quickly to a mixed *Pandanus-Metrosideros* forest which extends up to half a mile inland. This in turn gives way to Metrosideros forest which, though varying in height and understorey composition according to age, shows a general increase in species with increase in altitude. This trend reaches a maximum between 1500 and 2500 feet, the zone of highest rainfall, where scattered groups of the palm *Pritchardia bacheriana* occur in the Metrosideros canopy. In the understorey there are many small trees including *Psychotria* spp., *Cheirodendron trigynum*, *Ilex anomala*, *Gouldia terminalis*, and the tree-ferns *Cibotium splendens* and *C. glaucum*. At higher altitudes tree-ferns become increasingly important and between 3000 and 4000 feet theycompose the lower layer of a two-layered canopy in which Metrosideros is emergent.

On very recent flows the whitish-colored lichen *Stereocaulon vulcani* is often abundant and the only frequent tree seedling is *Metrosideros*. Introduced species are uncommon.

On pahoehoe flows the *Metrosideros* trees are usually smaller and more widely spaced. Between them and sometimes growing over them are dense thickets of gleichenia fern (*Dicranopteris linearis*).

Land-clearing, fires and introduced animals, particularly pigs and cattle, have modified or destroyed the original vegetation in many places allowing several introduced plants to become widespread. The most

Figure 3. Vegetation profile drawn parallel to Stainback Highway, Mauna Loa.

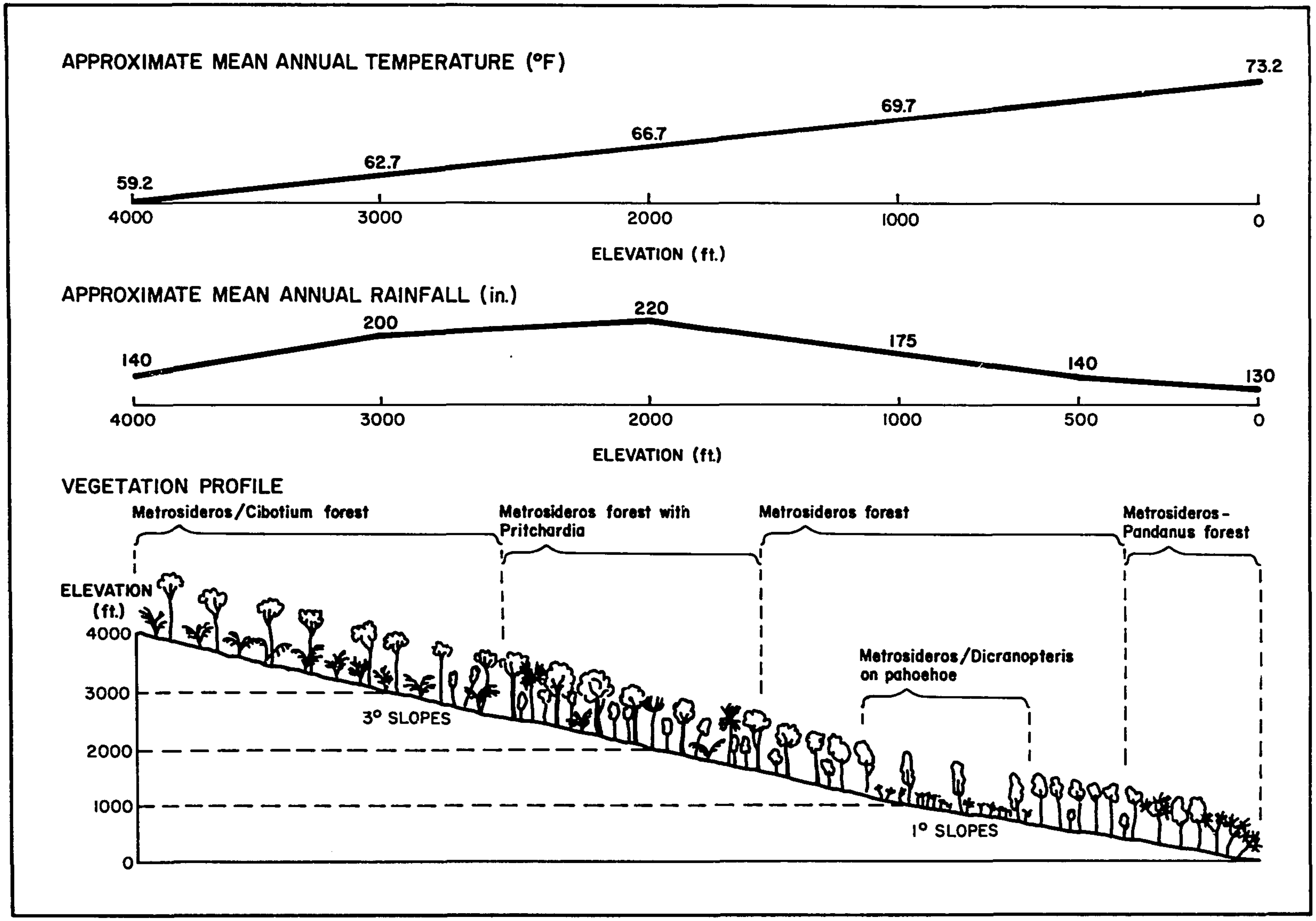
APPROXIMATE MEAN ANNUAL TEMPERATURE (°F)
59.2
62.7
66.7
69.7
73.2
4000
3000
2000
1000
0
ELEVATION (ft.)
APPROXIMATE MEAN ANNUAL RAINFALL (in.)
140
200
220
175
140
130
4000
3000
2000
1000
500
0
ELEVATION (ft.)
VEGETATION PROFILE
Metrosideros/Cibotium forest
Metrosideros forest with Pritchardia
Metrosideros forest
Metrosideros-Pandanus forest
Metrosideros/Dicranopteris on pahoehoe
ELEVATION (ft.)
4000
3000
2000
1000
0
3° SLOPES
1° SLOPES

TABLE 1. AVERAGE COMPOSITIONS OF THOLEIITIC BASALTS FROM MAUNA LOA AND KILAUEA

(From Macdonald and Katsura 1964)

Element as oxide	Mauna Loa 27 analyses	Kilauea 51 analyses
SiO_2	51.11 %	49.96 %
Al_2O_3	12.93 "	13.25 "
Fe_2O_3	2.63 "	1.88 "
FeO	8.80 "	9.75 "
CaO	10.03 "	10.60 "
MgO	8.79 "	8.39 "
TiO_2	2.52 "	2.86 "
Na_2O	2.19 "	2.26 "
K_2O	0.38 "	0.54 "
P_2O_5	0.24 "	0.30 "
MnO	0.14 "	0.16 "

abundant are guava (Psidium guajava), Pluchea odorata and Indian Rhododendron (Melastoma malabathricum).

In the drier Puna rift area, there are remnants of Pandanus and Pandanus-Metrosideros forests near the coast but along the shoreline itself grow thickets of naupaka (Scaevola taccada) and hau (Hibiscus tiliaceus). Modification of the forest is more obvious in this Pahoa area. Coconut groves and plantings of ironwood (Casuarina equisetifolia) and mango (Mangifera indica) are common. Also present are small groves of kamani (Calophyllum inophyllum) and kukui (Aleurites moluccana). A mixed secondary scrub of guava, Pipturus, Java plum (Eugenia cumini) and Pluchea has taken over in some parts.

Pahoehoe flows are more widespread in the Puna district where gleichenia fernlands with spaced Metrosideros trees are common. Around Pahoa large areas of this vegetation have been burnt; the regrowth is dominated by grasses, particularly Andropogon virginicus.

Land Use

Many of the prehistoric and historic flows in the study area below an elevation of 1000 feet are being cleared for house construction. Sugar-cane plantations are restricted to the relatively small areas of older soil but in the Puna district plantations of coconut, papaya, banana and coffee are growing successfully on recent lava flows. With addition of volcanic ash and fertilizers, a large macadamia nut farm (Macadamia integrifolia) has been established on the young flows of Mauna Loa north of Olaa.

At higher elevations adjacent to the Stainback Highway, the Metrosideros forest is being replaced by various forestry plantings: Queensland 'maple' (Flindersia brayleyana) and Australian red 'cedar' (Toona *ciliata*) are growing at altitudes up to 3000 feet. At higher altitudes towards 4000 feet there is flooded gum (*Eucalyptus saligna*), Australian blackwood (*Acacia melanoxylon*) and tropical ash (*Fraxinus uhdei*). Nevertheless, at these higher elevations there are still stands of Metrosideros forest which appear to have been little disturbed.

SAMPLING

Selection of Lava Flows

The flows studied were chosen because of their known age or relative youth, their position in a high-rainfall zone where weathering rates would be relatively fast, and their lack of recent ash additions (Fig. 1). Details of each flow sampled are given in Table II and published chemical analyses for samples of some of these flows are listed in Appendix 1.

Seven dated flows were sampled on Hawaii, one site per flow excepting two flows which had two sites each. All samples were collected between August 1967 and August 1968. During the first part of the study a chronosequence consisting of the 1942, 1881, 1855, and 1852 flows of Mauna Loa was sampled. It soon became clear that the pahoehoe flows of 1881 and 1855 could not be grouped with aa flows because of their slow rates of change. The Kilauea flows of 1955, 1840, and 1750 were then sampled in order to increase the number of aa flows and extend the time-span for measuring changes.

Four prehistoric flows were sampled on Hawaii: two flows on Mauna Loa adjacent to the Stainback Highway, one on the western side of Mauna Loa in the Honaunau district (limited sampling only) and one on a flow from the east rift of Kilauea in the Kapoho district.

In addition to the Hawaiian samples, some analyses were made of lavas collected from Western Samoa by Mr. C.L. Schroth (Dept. of Agronomy and Soil Science, University of Hawaii) during July 1968. One collection was from the 1760 pahoehoe flow on Savaii and the other was from a prehistoric pahoehoe flow on Upolu. The Upolu flow overlies a 5-foot

TABLE II. DETAILS OF LAVA FLOWS SAMPLED

Volcano	Name of Flow	No. of Samples	Alt. (ft.)	Mean ann. rainfall (in.)	Mean ann. temp. (°F.)	Type of Ecosystem
Kilauea	1955	10	930	100*	69.9*	*Stereocaulon* lichenfield
Mauna Loa	1942	10	3720	150	60.2	" "
" "	1881	4	3880	220	59.9	*Dicranopteris* fernland
" "	1855	5	3660	250	60.4	*Metrosideros/Dicranopteris* treeland**
" "	1852	10	3660	210	60.4	*Dicranopteris* fernland
Kilauea	1840H	10	650	130	70.9	*Metrosideros/Dicranopteris* treeland
"	1840L	10	40	115	73.1	*Metrosideros* rockland
"	1750H	10	990	110	69.7	*Metrosideros* forest
"	1750L	6	300	90	72.1	*Metrosideros* treeland
Mauna Loa	Upper Stainback	4	3780	140	60.0	*Metrosideros/Cibotium* forest
" "	Lower Stainback	5	300	140	72.1	*Metrosideros* forest
Kilauea	Prehist. Kapoho	5	90	105	72.9	*Pandanus* forest
Mauna Loa	Honaunau	3	3250	88	61.8	*Metrosideros* forest
Savai'i, Samoa	1760	5	550	125-150	77.0	Treeland
Upolu, Samoa	Prehist. Upolu	5	200	150-175	78.0	Forest

*Climatic data from Blumenstock and Price (1967)

**See p. 57.

TABLE II (Continued). DETAILS OF LAVA FLOWS SAMPLED

Name of Flow	Rock Type and Position of Sampling Site
1955	basalt; Puna aa. Approx. 5 miles south of Pahoa and ½ mile west of Pahoa-Kalapana road.
1942	basalt; Kau aa. Approx. 5 miles north-west of Stainback Highway along a forestry planting road and approx. 400 yards west of planting road.
1881	hypersthene-rich basalt; Kau pahoehoe. Approx. 13 miles west of Hilo and 1.9 miles south-east of Hilo-Kamuela saddle road along a forestry planting road.
1855	olivine basalt; Kau pahoehoe. Approx. 12 miles west of Hilo and 50 yards south of Hilo-Kamuela saddle road.
1852	oceanite; Kau aa. Approx. 13 miles west of Hilo and 2.6 miles south-east of Hilo-Kamuela saddle road along a forestry planting road.
1840H	oceanite; Puna aa. 1.8 miles east of Pahoa and 25 yards north of Pahoa-Kapoho road.
1840L	oceanite; Puna aa. Approx. 4.5 miles north-west of Kapoho and 25 yards south of road.
1750H	olivine basalt; Puna aa. Approx. 6 miles south of Pahoa and 2.5 miles west of Pahoa-Kalapana road. (3.4 miles west of 1955 flow).
1750L	olivine basalt; Puna aa. Approx. 7.6 miles south of Pahoa and 0.5 miles north-west of Pahoa-Kalapana road.
Upper Stainback	olivine basalt; Kau aa. 100 yards north of Stainback Highway and 13 miles from volcano road.

TABLE II (Continued). DETAILS OF LAVA FLOWS SAMPLED

Name of Flow	Rock Type and Position of Sampling Site
Lower Stainback	olivine basalt; Kau aa. 100 yards north of Stainback Highway and 0.6 miles from volcano road.
Honaunau	olivine basalt; Kau aa. Between 4 and 5 miles west of Kealakekua in the Honaunau Forest reserve.
Prehistoric Kapoho	basalt; Puna aa. 1.5 miles north of northern edge of Kapoho 1960 flow.
Savaii 1760 Samoa	alkalic olivine basalt; Aopo pahoehoe. Approx. 2 miles west of A'opo, Savai'i and 60 to 100 yards above road.
Prehistoric Upolu, Samoa	alkalic olivine basalt; Puapua pahoehoe. Approx. 1 mile east of Sa'agafou, Upolu, and 60 to 100 yards above the road.

raised beach which has been correlated tentatively by Kear and Wood (1959) with a New Zealand raised beach having a radiocarbon age of 2,220 ± 70 years (Fergusson and Rafter 1957, p. 38).

Type of Sample Collected

A section of rock from a flow more than 10 years old shows an irregular 'weathered crust'. This was most distinct in dense non-porous rock. In early stages of this study, a diamond saw was used to cut off the crust which became the weathered sample, while the central portion of the rock provided the 'unweathered' sample. However, it was difficult to remove the weathered crust without including variable amounts of less weathered rock.

An attempt to remove these crusts in a reproducible manner was made using ultrasonic vibration. A Bronwill Biosonick II high-intensity probe was run at 75% full power (= 90 watts of acoustic energy at 15 kcps) for 5 minutes. With 10-60 gm rocks from prehistoric flows, up to 0.6% by weight could be removed. With less weathered samples the rock removed was usually less than 0.1%, an insufficient amount for analysis.

For this reason, it was considered that small rocks might be more suitable for use as weathered samples. A group of small rocks (<2.5 cm diam.) from the surface of the 1750H flow were compared to the weathered crusts removed from large boulders, 0.5 to 1 meter in diameter on the same flow. pH measurements (see "Analytical Methods") were used as a basis for comparison.

Samples from site 1750H	No. of samples	Mean pH and stand. deviation	Probability
Weathered crusts from boulders	6	7.82 ± 0.10	$p < 0.01$
Small surface rocks	10	7.28 ± 0.23	

The lower pH values for small rocks suggested that these are weathering more rapidly and were therefore likely to be more sensitive indicators of small changes on very recent flows. Thus, further collection of weathered samples on aa flows was restricted to small rocks, 1.5 - 2.5 cm in diameter.

With pahoehoe flows, the early samples used for weathered material consisted of the glassy, often loose, surface crust usually less than 1 cm in thickness. However, further observation showed that this glassy crust was not always present and that its weathering was not typical of the upper part of a pahoehoe flow. Fe_2O_3 and X-ray diffraction analyses showed this material to be much more weathered than weathered rocks from aa flows thus making comparisons difficult. In subsequent samplings, weathered rock was collected from the upper 3 cm after first removing any glassy crusts.

Sample Variability

If sampling can be planned to reduce sample variation to a minimum, there is a greater chance of measuring significant differences in weathering rates between flows. Variation was tested for by calculating coefficients of variation for titanium and strontium analyses made on a collection of 4 samples from each of 5 flows (not reported in detail). Coefficients ranged from 0.4 to 8.6% with a mean of 4.6%. Weight loss measurements (see "Results") made on the same samples indicated that higher coefficients could be expected.

Apart from intrinsic variation in chemical composition of the lava, several factors influence the rate of weathering of a particular rock and thus contribute to sample variability. These include properties of the particular rock such as size and porosity, its depth, and its position relative to plants. These factors are investigated below by use of pH measurements. General development of the work showed that pH measurements were quite a sensitive index of weathering and therefore useful for this purpose (see "Analytical Methods": pH measurements). Both lower pH_{H_2O} values and higher ΔpH ($pH_{KCl} - pH_{H_2O}$) indicate an increased degree of weathering.

Variable content of organic matter which may influence variability is also discussed under "Analytical Methods".

Size of Rock Sample

With aa flows, the presence of crusts of more weathered rock would lead one to expect that the proportion of weathered to unweathered rock would change with size of rock, the larger rocks having a larger amount of unweathered material. The pH of 10 rocks 1.3 to 3.8 cm diameter and collected from the same site (1750H) was measured but the results (Table III) showed no relation between size and pH. Thus in this range, size is unlikely to be a factor affecting sample variation.

Porosity of Rock Sample

To ascertain whether there was any relation between porosity and weathering, the pH of 6 unweathered rocks from the 1852 Mauna Loa flow was measured (Table IV). Three rocks (1852U) of typical porosity for the site were compared to three rocks having markedly greater porosities (1852P1-P3). Sample P3 was highly vesicular and the only member of the series that appeared more weathered judged by pH_{H_2O} measurements. Excepting highly vesicular rocks, excluded during subsequent sampling, porosity does not appear to be an important factor affecting sample variation at a site. However, differences in porosity between lava

TABLE III. ROCK SIZE AND pH

Small Rocks Collected from Surface of Site 1750H

Rock Weight (gm)	Average Rock Diam. (cm)	pH_{H_2O}
56.4	4.0	7.11
29.0	3.0	7.62
20.1	3.0	7.24
16.4	3.0	7.64
14.3	2.5	6.98
10.4	2.5	7.11
7.8	2.0	7.38
3.5	1.5	7.41
3.0	1.5	7.04
2.1	1.5	7.41
	Mean:	7.28

TABLE IV. EFFECT OF ROCK POROSITY ON pH

Sample	No. of Rocks	Est. % Surface Occ. by Pores	Est. Mean Pore Diam.	Rock Density	pH_{H_2O}	ΔpH*
1852U	3	25-50	$<$ 0.25mm	2.65g/cc	9.54	- 0.01
" P1	2	75-100	0.25 "	1.22 "	9.33	- 0.06
" P2	2	75-100	1.0 "	1.62 "	9.66	- 0.01
" P3	2	75-100	2.0 "	1.54 "	9.01	- 0.28

* $pH = pH_{KCl} - pH_{H_2O}$

flows were estimated for each set of samples (p. 47).

Depth of Rock Sample

Further pH measurements were made comparing a group of rocks buried in humus at a depth of 5 to 8 cm to surface rocks collected at the same place.

1750H Site	pH_{H_2O}	
Surface (10 samples)	7.10	$p < 0.05$
5 - 8 cm (5 samples)	7.71	

These results show that, judged by pH_{H_2O} values, buried rocks are less weathered than those at the surface. The same trends were noticeable in a comparison of buried and exposed portions of large rocks although in this case the number of samples was too small to make the difference statistically significant.

From these measurements it appears that depth of sampling should be held constant. Surface rocks were selected because of their more weathered condition.

Plant Cover

Using the 1750 aa flow, a comparison was made between surface rocks from under Metrosideros trees and those from a bare part of the flow less than 25 meters away (Table XX). The results indicate that weathering is more rapid under a Metrosideros cover.

However, samples collected from underneath the trunk and root system of uprooted trees were found to be much less weathered than those collected from among the roots, some distance from the trunk (Table XXI). To eliminate these sources of variation, samples were collected from among tree roots at a distance greater than 1 meter from the trunk but still under the tree crown. Whenever possible, samples were collected from under Metrosideros polymorpha trees so that any differences resulting from different plant species were avoided.

To summarize, when collecting aa basalt samples from high rainfall areas for weathering studies, it appears that of the factors investigated, depth of sample and position relative to trees are the most important; they should be kept constant as far as possible.

Sampling of Flows

Sampling Area

For each flow the general area for sampling was selected by choosing an altitude where rainfall and temperature were most similar to other flows studied so that comparisons would be facilitated. The final selection of a sample area depended on convenience of access.

Sampling Sites

At each flow, the exact location of the sampling site was determined by sighting at right angles across its general slope to a distant object and then, following this line, stepping out 50 paces from the edge of the flow. This was done to avoid bias and ensure that the sampling site was not influenced by any conditions peculiar to the flow edge. Having stepped the 50 paces, the site was checked to see if:

(i) its general slope was less than 10% (so that slope is relatively constant throughout sampling), and

(ii) its surface and vegetation were representative of the flow in that area.

If these conditions were not met, another 50 paces were traversed, and repeated if need be until a suitable site was reached.

The place where the pacing ended became one end of the sampling line which was maintained in the same direction as before. Using a table of random numbers, 5 to 20 sampling points were found at random distances between 7 and 15 paces apart along this line. At each sampling point, a sample was collected 1 to 2 meters from the trunk of the nearest *Metrosideros* tree that had a crown in the canopy layer and which was growing on a well-drained micro-site of gentle slope. On very young flows the sample was collected from a point within 1 meter of a *Metrosideros* seedling.

On one Hawaiian flow, the prehistoric Kapoho, absence of *Metrosideros* trees necessitated collection from beneath Pandanus (*Pandanus tectorius*) trees.

Samples from the Samoan flows were collected as described in this section but the trees of these sites have not been identified.

Weathered and Unweathered Samples from Aa Flows

Each sample consisted of two subsamples both collected from the surface of the flow: a 'U' subsample representative of the 'unweathered' (= least weathered) original rock and a 'W' subsample representative of the weathered rock.

The *'U' subsample* was obtained by knocking out a cube of rock approximately 3 x 3 x 3 cm from the center of a boulder 30 to 60 cm in diameter using a sledge-hammer and geologist's hammer. With some of the older flows it was difficult to find an 'unweathered' sample because of the amount of weathering that had occurred. On the two Stainback prehistoric sites and the 1750L flow, the 'U' subsamples were obtained by knocking out portions of much larger boulders. These had been recently split during construction of a power-line access road and were within 100 yards of the sampling site.

The 'W' subsample was obtained by collecting several small weathered stones (between 1.5 and 2.5 cm diameter) to approximately equal the weight of the 'U' subsample (usually 3 to 5 stones). Very vesicular stones if atypical of the site were not collected. With the 1852 and 1840H sites the scarcity of small stones necessitated collection of small protuberances and weathered crustal fragments of larger rocks in order to get an adequate 'W' subsample.

Weathered and Unweathered Samples from Pahoehoe Flows

At each sampling point, a sample was collected from the nearest spot beneath a Metrosideros tree where the lava surface is fissured enough to allow one to prise out a lava block at least 20 cm (8") in thickness.

The 'U' subsample was collected by knocking out a cube of rock approximately 3 x 3 x 3 cm from the lava block at a depth of 16 - 20 cm below the surface.

The 'W' subsample was collected by first removing any thin glassy crust present and then knocking out a similar-sized cube of rock from the uppermost 3 cm of the remaining block.

ANALYTICAL METHODS

Vegetation Analyses

Tree Density and Mortality

Tree density was obtained by counting the trees higher than 1 meter in a 30 x 2 m belt transect along the sampling line. A mortality count was obtained by counting standing dead trees in the same transect. If the number of live trees was less than 20, the transect was extended to give a more adequate sample.

Tree Volume Estimates

Tree volume estimates (V) were calculated from the relationship $V = ht \times \text{basal area}$, where basal area = πr^2 and r, the trunk radius, is obtained from the diameter breast height (d.b.h.) measured 4.5 feet above the ground. Tree heights were estimated by eye, excepting a few that were measured by abney-level, and shorter trees measured with a 3 m pole. The stem diameter of trees less than 1.5 m high was measured half-way up the stem.

Mean tree volumes, for the number of trees measured on each site, were expressed in cubic decimeters of tree growth per century and used as a measure of the rate of succession.

Cover

The term canopy is used here to denote the plant crowns that form the skyward surface of the vegetation. The term can be applied to any type of vegetation, e.g. lichenfield, fernland, or forest.

The percentage of ground area covered by the canopy (canopy cover) and the percentage covered by each species in the canopy was measured by recording the plants, if any, growing vertically above 50 points spaced 2 m apart along the sampling line (100 m transect). For shorter vegetation such as fernland, the 50 points were spaced at 60 cm intervals along a 30 m transect.

Floristic Composition

A list was made of all pteridophyte and spermatophyte species represented by 3 or more plants on each site, i.e. in an area some 50 x 50 m.

Metrosideros Juveniles

The number of juveniles (plants less than 1 m high) of *Metrosideros polymorpha* were recorded as below:

A = Abundant . . . . 5 or more individuals seen on the site (50 x 50 m).
I = Infrequent . . . Less than 5 individuals seen.
N.O. = None observed.

On a few sites, there were sufficient numbers of *Metrosideros* trees present to allow a height-class analysis that also gave information on juvenile numbers.

Stratification

Profile Diagrams: On some sites, profile diagrams were prepared by drawing all the plants greater than 0.5 m high that were present in a belt transect 2 m wide and 20 or 30 m long. The length depended on what was required to illustrate the structure of the vegetation. These profiles were used as an aid in estimating the depths of plant crowns.

Vegetation Strata: Floristic change during early stages of lava-flow successions in Hawaii involves only the addition of a few species whereas the amount of structural change, from lichens to a scrub forest, is much greater. Since a measure of this structural change was required, the degree of stratification as indicated by stratum depth, defined below, was chosen as a suitable criterion.

Objective criteria for distinguishing vegetation layers or strata are not easy to define and are seldom given in the literature although Newman (1954) did attempt to clarify this matter.

In this study a vegetation stratum is defined as a horizontal zone of plant crowns, of one or more species, that:

(i) forms a surface of foliage that is distinctly separate from the crowns of taller plants for at least half its area, and

(ii) covers, when projected vertically downwards, 10% or more of the ground surface.

In practice, many strata are so clearly defined that sampling to test for these criteria is not always necessary.

Crown depths of plants occurring in the line transects or profile diagrams were estimated from the depth or thickness of a plant's foliage. The mean depth or thickness of a stratum was obtained from the mean depth of all plant crowns sampled in the particular stratum.

The figures given in the "Results" section for total stratum depth were obtained by adding the depths or thicknesses of all strata present that exceeded 0.5 m in thickness. Rates of structural succession were expressed as total stratum depths / century.

Soil Profiles

Where profiles were sufficiently developed, profile descriptions were made following the methods of the Soil Survey Manual (Soil Survey Staff, 1951).

In order to obtain a more representative sampling of the depth of the organic horizon (excluding loose litter), 20 measurements at 2 m intervals were made along the sampling line for 40 m using a tubular auger.

Preparation of Rock Samples for Analysis

Removal of Organic Matter

Each weathered rock was brushed with a toothbrush to remove lichens, moss and fine roots. If roots were abundant the rocks were dried for 2 - 3 hours at 105° C. to loosen the roots before brushing. All rocks were subjected to 10 minutes of low-intensity ultrasonic vibration under water to remove any surface humus still adhering.

Following grinding, some rocks treated with hydrogen peroxide showed a reaction indicating that some organic matter had been present. This was probably composed of very fine roots that had penetrated pores in the rock, and humus. Attempts were made to remove the organic matter by the following procedures: flotation in water, flotation in carbon tetrachloride, centrifuging, high-intensity ultrasonic dispersion, and addition of a chelating resin. With some samples reweighing after treatment showed that all methods resulted in loss of some fine inorganic material in addition to organic matter. Rather than risk loss of clay-size particles, only superficial roots and humus were removed using the simple cleaning procedure described above. However, the amount of humus remaining within the rock is likely to increase with weathering whereas the amount surrounding a rock would be highly variable.

It may be noted that the zero values for cation exchange capacity, measured in weathered rocks from the Stainback flow (p. 93), suggest that the amount of organic matter present in these samples was very small.

Crushing and Grinding

All rocks were crushed in a 1 inch diameter steel mortar and passed through a 2 mm sieve. A glass vial containing a small magnet was run over the sample to remove any steel fragments present. By raising and lowering the magnet in the vial, it was found possible to separate the steel fragments from magnetite particles, which were less strongly attracted, and return the magnetite to the sample.

For grinding, a Pitchford Model 3800 vibratory grinder was used with a cylindrical shaker and ball both of tungsten-carbide steel. Enough sample to provide 5 to 10 gm of powder was ground for 3 minutes and passed through a 100 mesh sieve. Any particles remaining on the sieve were returned to the shaker for further grinding. After grinding, the samples were stored in small glass vials.

Density, Porosity and Texture Measurements

Specific gravity measurements of rock particles (100 mesh size) were made using the method of Wright (1934). Rock density (= bulk density of individual rocks) was measured using immersion in paraffin wax following the procedure of Blake (1965).

An attempt to use rock density as a means of characterizing rock porosity was unsuccessful because although highly vesicular rocks tended to have low densities, other rocks of apparently very different porosities were found to have similar densities. For this reason, the percentage area of the rock occupied by pores was estimated using a 10 x hand lens as follows:

Porosity	Rating
No obvious pores	0.0
< 10% of surface with pores	0.5
10-25% " " "	2.0
25-50% " " "	4.0
50-100% " " "	7.5

Texture of rock samples was assessed with the aid of a hand lens according to the following scheme:

Texture	Rating
No phenocrysts > 0.5 mm diameter	10.0
0-5% surface occupied by phenocrysts > 0.5 mm diam.	9.0
5-20% " " " " " "	7.0
20-50% " " " " " "	4.0
50-100% " " " " " "	2.5

pH and Cation Exchange Capacity Measurements

pH Measurements

Stevens and Carron (1948) describe a method of grinding mineral fragments under water to make a heavy suspension and then, using indicator papers, measuring the "abrasion pH" of the suspension. They found pH values varying from 1 to 12 for various minerals with felspars, pyroxenes, amphiboles and olivine falling in the range 8 to 11.

In the present study, rock pH was determined by measuring the pH in water and in KCl. A 1:1 suspension of 100 mesh rock powder and distilled water (2 gm rock : 2 ml water) was equilibrated for 1 hour at 23°C., stirred and tested for pH 60 seconds later. Approximately 0.15 gm of KCl was then added to make a 1N KCl concentration and the suspension allowed to equilibrate for another hour. pH measurements were repeated and the $pH_{KCl} - pH_{H_2O}$ difference recorded as ΔpH.

Samples of partly decomposed litters from several plant species were also tested for pH using 20 g of litter to 20 ml of distilled water and 1 hour's equilibration. This measurement is referred to subsequently as litter pH.

For all these measurements an Orion model 801 digital pH meter with expanded scale was used together with a Beckman 39142 combination electrode containing glass and reference electrodes in the same assembly. With this instrument an accuracy of ± 0.025 pH units can be obtained. The 5 ml plastic vials used to hold the suspensions were shielded from electrical interference by an earthed aluminum foil shield during measurement.

Cation Exchange Capacity Measurements (C.E.C.)

C.E.C. measurements were made on 2 gm samples of 100 mesh rock powders. The samples were placed in porous porcelain crucibles and leached under suction 5 times with 50 ml portions of 1N calcium acetate. This calcium-saturated rock was washed 5 times with 50 ml portions of distilled water and then filtered with 100 ml of ammonium acetate. The calcium removed was measured by titration with E.D.T.A.

Hydration Measurements

Weight-loss Measurements

One gram samples of 100 mesh rock powder were weighed into 2 inch diameter vycor glass dishes and dried overnight at 110°C. They were then weighed and placed in a muffle furnace at 350°C. for 24 hours and the resulting weight loss expressed as a percentage of the 110°C. weight. This weight loss on heating is largely sorbed water and hydroxyl water

(Jackson 1956) together with CO_2 losses from any organic matter present. Small weight gains, up to 0.3% were observed at higher temperatures, presumably related to ferrous-ferric ion oxidations. Thus measurement of the hydroxyl water loss that occurs up to and above 500°C. was not attempted.

Rehydration Measurements

With one group of samples, after the 110-350°C. weight-loss measurements had been completed, the weight increases were measured following equilibration for 1-3 days at 50%, 79.3% and 98% relative humidities. Desiccators were used with 43% H_2SO_4 to maintain 50% R.H. and saturated solutions of NH_4Cl and $CuSO_4.5H_2O$ for 79.3% and 98% R.H. respectively.

Hydration-rind Examination

Friedman's (1968) method of examining the hydration rinds of obsidian in rhyolite flows prompted a search for volcanic glass in some of the basalt flows studied. Two or three smooth-skinned lava droplets that appeared to have been rapidly cooled were collected from each of 4 flows. Thin sections were cut across each droplet, using standard procedures, mounted on slides, and ground down to allow a microscopic search for any hydrated glassy surfaces.

Oxidation Measurements

The method used was that of Bardossy and Bod (1961) who characterized the oxidation state of sedimentary rocks by dissolving them in a strong oxidising agent - potassium dichromate. The change in the base potential of the dichromate is taken as an indirect measure of the oxidation state of the rock. The greater the change, the more reduced was the rock.

100 ml portions of 0.01N and 0.001N $K_2Cr_2O_4$ were added to 1 gm amounts of 100 mesh rock powder together with 2 ml 48% sulphuric acid to stabilize the pH below 1. The solutions were continually agitated on a vibratory shaker and e.m.f. and pH measurements made at 0, 1, 3, 18, and 24 hours. A Beckman pH meter (expanded scale) with inert platinum and calomel reference electrodes was used. Changes in pH that occurred during the 24-hour period were corrected by using the Nernst equation.

Mineralogical Measurements

X-ray diffraction patterns of powder samples were obtained using a Norelco X-ray wide range diffractometer and Geiger-Muller tube detector. The instrument conditions used were a scanning speed of 1 degree 2θ per minute, chart speed of $\frac{1}{2}$ inch per minute, divergent, scatter, and receiving slits of 1°, 1° and 0.006 inch respectively, tube voltage of 35 kv, current 20 ma, and copper radiation with nickel filter. The range 25 to 37° 2θ was scanned to trace out plagioclase, pyroxene, olivine and iron oxide peaks.

Two attempts were made to determine magnetite / maghemite ratios. The same diffractometer was used with an autofocus attachment (AMR 3-201) that curves the specimen so that its surface is coincident with the goniometer focussing circle at all diffraction angles, thus increasing resolution. Using a procedure outlined by Montagne (unpubl.), the 100 mesh samples were ground in acetone with a porcelain mortar and pestle to a size <400 mesh and brushed onto a fiberglass slide. Four drops of collodion were added andthe fine powder air-dired for 10 minutes before mounting. The instrument conditions used were scanning speeds of 0.5 and 1 degrees 2θ per minute, chart speed of $\frac{1}{4}$ inch per minute, divergent, scatter, and receiving slits of 4°, 4° and 0.006 inch respectively, tube voltage of 35 kv, current 10 ma, and iron radiation without filter. The range of 10 to 58° 2θ was scanned.

A second approach for determining magnetite / maghemite ratios was by using a magnetic susceptibility recorder designed and built by Gilliard (unpubl.). This auto-recording analytical balance records changes in weight of the sample as it is heated in a magnetic field of 4400 gauss to 700°C. and cooled in the same field.

Elemental Analyses

Extraction

The fusion technique of Suhr and Ingamells (1966) was used to obtain solutions for analyses of Si, Al, Ca, Mg, K and Na. From 0.1 to 0.2 gm of 100 mesh rock powder was weighed accurately and mixed with 1 gm of lithium tetraborate and fused in a carbon crucible at 940°C. for 15 minutes. The melt was poured into 60 ml of 1:25 nitric acid in a teflon beaker and stirred until dissolved (15 to 30 minutes) with a teflon-covered stirring bar. Each solution was filtered to remove teflon and carbon fragments before being made to 100 ml. vol. with dilute nitric acid (1:25).

Silicon and Aluminum

Silicon was determined within 8 hours of extraction using the method of Shapiro and Brannock (1962). Silicon was measured by colorimeter after development of a molybdenum blue color. Aluminum determinations were made within 24 hours of extraction using the aluminon procedure of Hsu (1963). Preparation of silicon and aluminum standards followed the recommendations of Jackson (1958).

Calcium and Magnesium

These determinations were made by atomic absorption spectroscopy using an air-acetylene flame. To diminish interference from aluminum, sufficient lanthanum oxide was added to make a 1% concentration in the test solution. Aliquots from a blank tetraborate fusion were added to the standards and all final dilutions made with distilled water. Accuracy and precision were tested by making duplicate determinations on a set of Hawaiian Institute of Geophysics (H.I.G.) rock standards as well as duplicate determinations for some samples of each flow.

Sodium and Potassium

These elements were determined using aliquots of the tetraborate extracts and a Beckman DU flame photometer. Accuracy and precision were measured as above by making duplicate determinations on H.I.G. standard rocks and duplicating some of the unknown samples.

Iron

Iron was determined as Fe_2O_3 under contract by the Rocky Mountain Geochemical Corporation using 100 mesh rock powders and atomic absorption spectroscopy.

Titanium

Titanium was determined by X-ray fluorescence using a Norelco Universal Vacuum spectrometer and FA-60 tungsten anode X-ray tube at 50 kv and 40 ma. The 100 mesh rock samples were poured into aluminum sample holders equipped with 0.0005 inch Mylar windows and the holder gently tapped to ensure an even distribution of rock powder over the window. A pulse-height analysis plot of the $TiK_{\alpha 1}$ peak was made to select settings of 6.5 volts for level and 9v for width thus excluding higher orders of X-rays. Counting strategy was based on that of Price and Angel (1968) who used the spectrum of the chromium anode as an internal standard. In the present case count rates of $TiK_{\alpha 1}$ peak and $WL_{\alpha 1}$ were measured using a LiF analysing crystal and flow-proportional counter (P-10 gas) with detector voltage of 1600. The $TiK_{\alpha 1}/Wl_{\alpha 1}$ ratio was plotted against the titanium concentrations of the H.I.G. standard rocks (Fig. 4) and similar ratios of the unknown rocks interpolated on the standard curve obtained. A rock standard was kept in the same sample holder throughout the measurements and counts made on it between every three unknowns so that fluctuations in the counting rate of the machine could be corrected for.

Strontium

This element was also determined by X-ray fluorescence using a tungsten-anode at 50 kv and 40 ma with scintillation counter and detector voltage of 1060. Samples were placed in sample holders similarly to the method used for titanium but the counting strategy of Champion et al (1966) was followed with counts made of the SrK_{α} peak (25.23° 2θ) and at two points either side of the Sr peak (23.5 and 26.5° 2θ) to obtain a background count. The ratio R of net peak to background was calculated using the formula:

$$R = \frac{n_p}{n_b} - 1$$

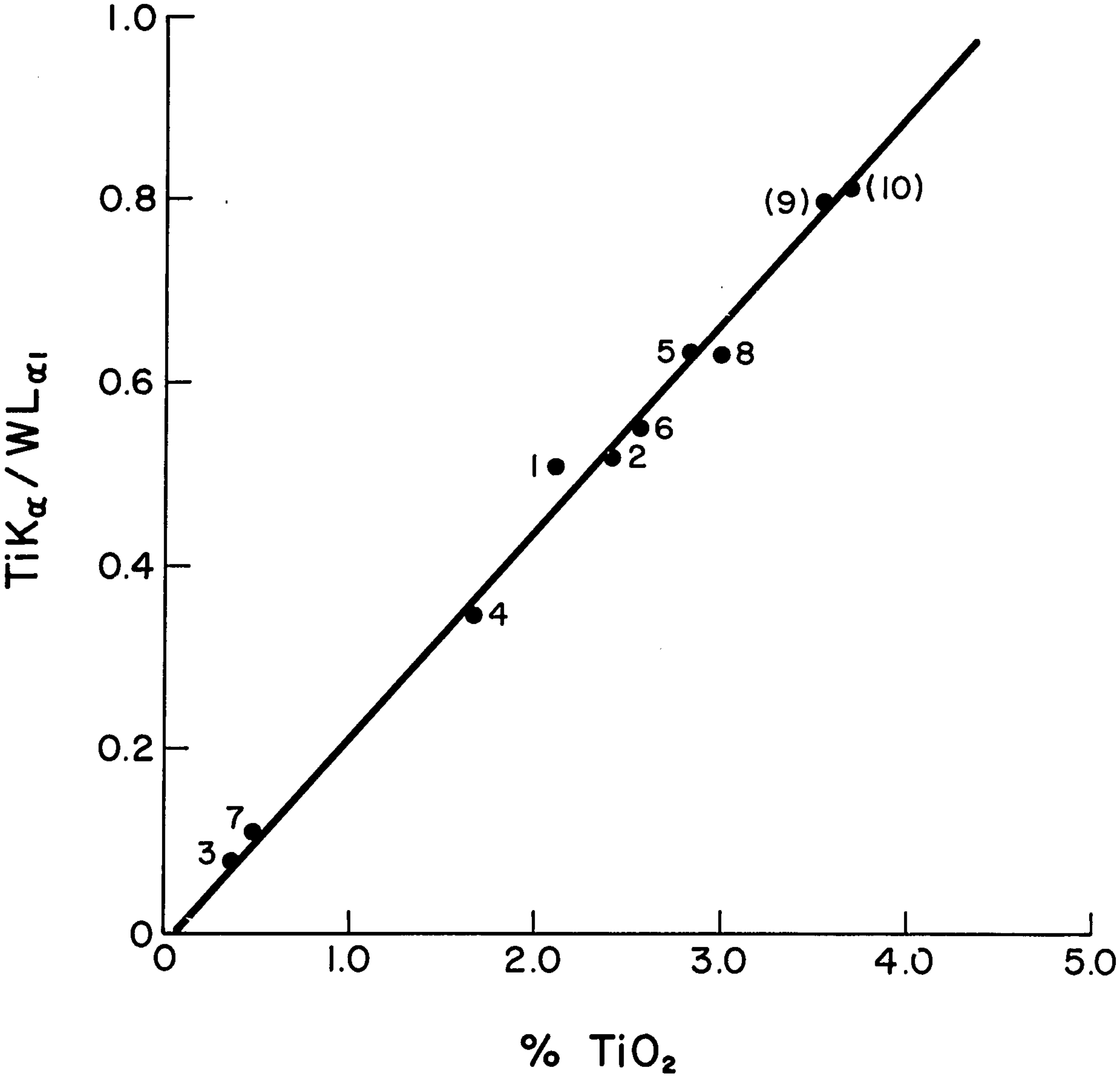
where n_p is the count rate at the peak position

and n_b is the interpolated background count rate at the peak position.

Manganese and Nickel

Similar methods to those used for strontium were applied to manganese and nickel except that a titanium filter was used with the tungsten tube in order to exclude X-ray interference from elements of lower atomic number.

Figure 4. Standard curve for titanium. (X-ray fluorescence determinations of H.I.G. standard rocks; analyses are mean values from Japanese Analytic Laboratory and U.S. Geological Survey).


1.0
0.8
0.6
0.4
0.2
0
$TiK_\alpha / WL_{\alpha_1}$
0
1.0
2.0
3.0
4.0
5.0
% TiO_2
1
2
3
4
5
6
7
8
(9)
(10)

Treatment of Results

Accuracy and Precision

Accuracy was determined from the difference between the reported analysis for the standard rock and the measured value, divided by the standard rock figure. The precision of duplicate determinations was determined from the relationship:

$$\frac{\text{larger value - smaller value}}{\text{mean value}}$$

Accuracy and precision figures given in the results section are means and standard deviations with the number of determinations on which each mean is based, placed in parentheses.

Variation, Losses and Gains

Standard deviations (S.D.) are used in the tables to indicate the variation between samples from the same flow. The heading 'No.' refers to the number of samples measured. A standard t test (Snedecor 1956) was used for testing the significance of the differences between weathered and unweathered rocks. The symbol 'p' is used for the probability of error if the null hypothesis is rejected. All differences that fall below the 90% level of significance (p = 0.1) are listed as not significant (N.S.). For differences equal to and greater than this level of significance, percentage losses or gains were calculated by expressing the differences between measurements for weathered and unweathered rocks, as percentages of the measurement for the unweathered rocks.

Regression Analyses

This work was carried out at the University Computing Center using an IBM 360/65 computer. Correlation matrices and regression equations were obtained using a stepwise multiple regression program (BMDO2R) based on that of Efroymson (1960).

RESULTS AND DISCUSSION

Vegetation Changes

Succession

In this section, emphasis will be given to field observations made on many flows, in addition to those sampled. The sampling results (Tables V - VIII) are discussed more fully in the Discussion and Conclusions section (p. 138). The list of species found on the sampling sites is given in Appendix III.

In naming the ecosystems sampled (Table V), terms such as forest, lichenfield and rockland are used according to whichever type of growth-form or ground material constitutes most of the uppermost surface. The term 'treeland' rather than forest is used for a tree-dominated ecosystem if the canopy cover of trees is less than 80%. The type of forest or fernland is designated from the generic names of the major canopy species, i.e. those with canopy cover equal or greater than 20%. An "/" sign between generic names indicates that the first species (e.g. *Metrosideros*) forms a separate stratum *above* the second species (e.g. *Dicranopteris*). (A hyphen separates species in the same stratum). Use of this naming system enables one to convey concisely information on composition and structure of the ecosystem.

Field observations indicate that four successional trends can be distinguished:

1. *Rockland → Metrosideros treeland → Pandanus forest:* This trend is restricted to the coastal zone having more than 70 inches annual rainfall. It occurs on both pahoehoe and aa flows. Within 5 years of flow formation, swordfern (*Nephrolepis* sp.) and the lichen *Stereocaulon vulcani* become

TABLE V. COMPOSITION AND TYPE OF ECOSYSTEM SAMPLED

Flow	Altitude (ft.)	Type of Ecosystem	Principal Species	No. of Species	Metrosideros Juveniles
1955	930	*Stereocaulon* lichenfield	Stereocaulon, Metrosideros	7	A*
1942	3720	" "	" Rhacomitrium	15	A
1881	3800	*Dicranopteris* fernland	Dicranopteris, Machaerina, Lycopodium, Metrosideros	14	A
1855	3660	*Metrosideros/Dicranopteris* treeland	Metrosideros, Dicranopteris, Stereocaulon, Lycopodium	12	A
1852	3660	*Dicranopteris* fernland	Dicranopteris, Metrosideros, Machaerina	14	A
1840H	650	*Metrosideros/Dicranopteris* treeland	Metrosideros, Dicranopteris	13	N.O.*
1840L	40	*Metrosideros* rockland	" Stereocaulon	17	A
1750H	990	" forest	" Diospyros	20	N.O.
1750L	300	" treeland	" Stereocaulon	14	I*
Upper Stainback	3780	" /*Cibotium* forest	" Cibotium	19	N.O.
Lower Stainback	300	" forest	" " Coffea, Freycinetia	12	N.O.
Honaunau	3250	" "	Metrosideros, Cibotium	-	I
Prehistoric Kapoho	90	*Pandanus* forest	Pandanus, Psidium, Cordyline	11	N.O.

*A = abundant; I = infrequent; N.O. = not observed established. The lichen does not form the thick crusts that can be found on some inland sites. Metrosideros polymorpha is the pioneer tree species, appearing within 10 years, and an open treeland develops as on the 1840L site (Fig. 5). The height-class distribution of Metrosideros on this site is shown in Table VI. Establishment of young Metrosideros is still occurring on this open site, even after 120 years. Since Pandanus tectorius is absent from the 1750 flow it must sometimes be more than 200 years before this species enters the community. However, on late prehistoric flows between the 1750 flow and the 1960 Kapoho flow, juvenile Pandanus can be seen among the Metrosideros (Fig. 6). On older prehistoric flows, both between and south of these flows, Pandanus-Metrosideros forests occur. In advanced stages of the succession, Metrosideros decreases and may disappear as on the prehistoric Kapoho flow (Table V, Figs. 7, 8).

TABLE VI. HEIGHT-CLASS DISTRIBUTION OF METROSIDEROS POLYMORPHA

	Lava Flow					
Height Class	1955	1942	1881	1855	1852	1840L
0-1 meters	100%	95%	59%	28%	7%	5%
1-2 "		5	17	33	26	10
2-3 "			13	19	36	5
3-4 "			6	11	25	55
4-5 "			2	3	3	15
>5 "			3	6	3	10
No. of Plants Sampled	25	60	63	36	61	20

Figure 5. Profile diagram of *Metrosideros* rockland on the 1840L (aa) sampling site, Kilauea : 40 ft. elevation.

(M = *Metrosideros polymorpha*, N = *Nephrolepis hirsutula*,
S = *Scaevola taccada*.)

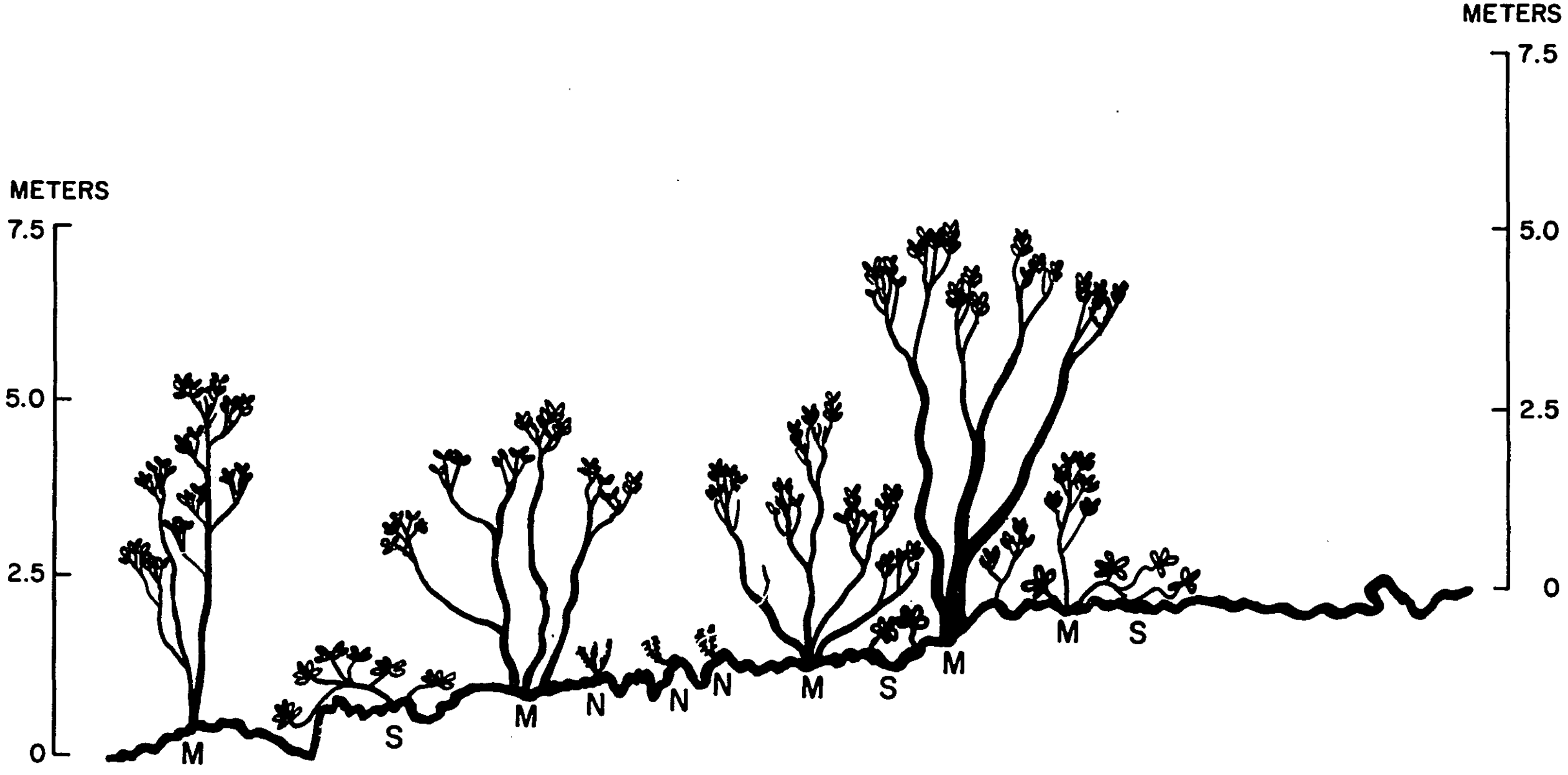

METERS
7.5
5.0
2.5
0
M
S
M
N
N
N
M
S
M
M
S
METERS
7.5
5.0
2.5
0

Figure 6. <u>Metrosideros</u> treeland with juvenile <u>Pandanus</u> on aa flow, Kapoho district : 50 ft. elevation.

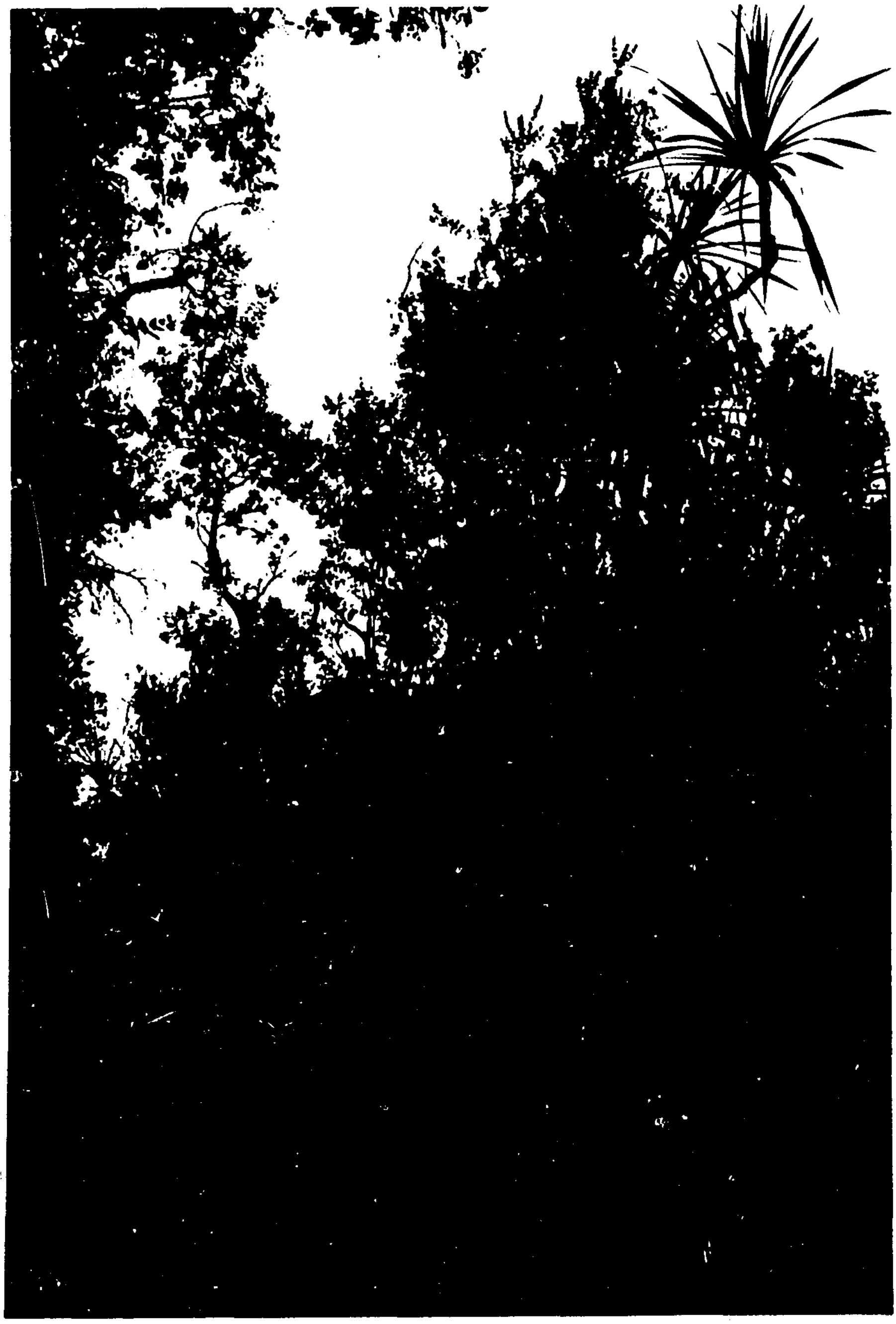
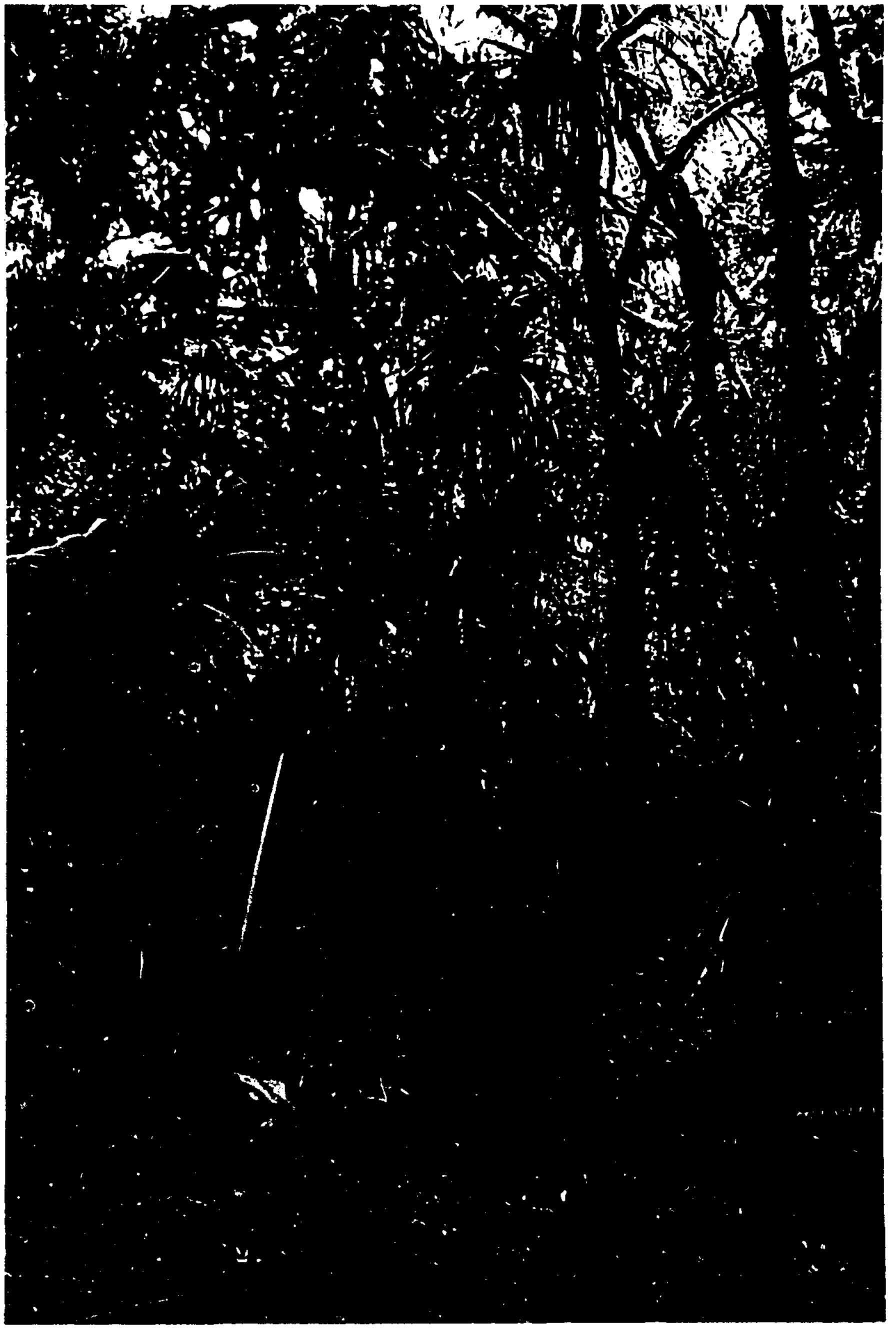


Figure 7. Profile diagram of *Pandanus* forest on the prehistoric Kapoho (aa) sampling site, Kilauea : 90 ft. elevation.

(A = *Aleurites moluccana*, An = *Asplenium nidus*,
Mc = *Morinda citrifolia*, P = *Pandanus tectorius*,
Pg = *Psidium guajava*).


METERS
10.0
7.5
5.0
2.5
0
METERS
12.5
10.0
7.5
5.0
2.5
0
P
A
An
P
A
P
P
Mc
An
Pg
P
Pg
P
P P

Figure 8. Pandanus tectorius forest, prehistoric Kapoho (aa) sampling site, Kilauea : 90 ft. elevation.



2. *Rockland → Dicranopteris fernland → Metrosideros forest:* Below 1000 feet elevation this is by far the most widespread trend of succession on both aa and pahoehoe flows. The earliest stages have been described in detail by Doty (1967). Mats of *Stereocaulon* are usually very prominent on young flows. During intermediate stages of the succession there is wide variation in the proportions of *Dicranopteris linearis* and *Metrosideros* forming the canopy and all gradations from fernland to treeland can sometimes be found on the same flow. The 1840H site (Tables V, VII) exemplifies an intermediate stage while the Lower Stainback stand shows a much later stage in which the *Dicranopteris* has disappeared (Fig. 9). This stand has an understorey of *Cibotium* tree-ferns, *Psidium guajava* and *Coffea* sp. The rather dense spacing of the *Metrosideros* and comparatively small mean tree volume (Table VIII) suggest that the Lower Stainback forest may be secondary growth following fire. No burnt stumps were noticed but charcoal was found in a soil profile about 100 feet altitude lower in an area of similar rainfall.

Juvenile *Metrosideros* plants were not present on either the 1840H or Lower Stainback sites, possibly because of the dense fern cover in the first case and the dense understorey in the second.

3. *Rockland → Dicranopteris fernland → Metrosideros/Cibotium forest:* This trend is found in the higher rainfall zone between 1000 and 4500 feet elevation. It is essentially similar to the second successional trend discussed above but differs in that *Cibotium* tree ferns form a major part of the canopy during later stages. The increased *Cibotium* cover is probably related to the higher rainfall rather than the lower temperature conditions at these higher elevations. Among the sites

TABLE VII. VEGETATION STRATIFICATION

Flow	No. of Strata and Major Components	Maximum Height (m)	Mean Heights of Plants in Strata (m)	Mean Depths of Strata (m)	Total Stratum Depth (m)
1955	1) Metrosideros	1.2	0.3	0.3	0.3
1942	1) "	2.0	0.4	0.4	0.4
1881	1) "	9.0	2.0	1.7	2.2
	2) Dicranopteris		0.6	0.5	
1855	1) Metrosideros	7.0	2.1	2.0	2.3
	2) Dicranopteris		0.4	0.3	
1852	1) Metrosideros	7.0	2.2	2.0	3.2
	2) Dicranopteris		1.3	1.2	
1840H	1) Metrosideros	9.0	7.5	5.0	6.0
	2) Dicranopteris		1.5	1.0	
1840L	1) Metrosideros	6.7	3.5	3.0	3.0
1750H	1) "	24.0	21.0	9.1	16.7
	2) Diospyros		10.7	7.6	
1750L	1) Metrosideros	12.0	10.7	10.0	10.0

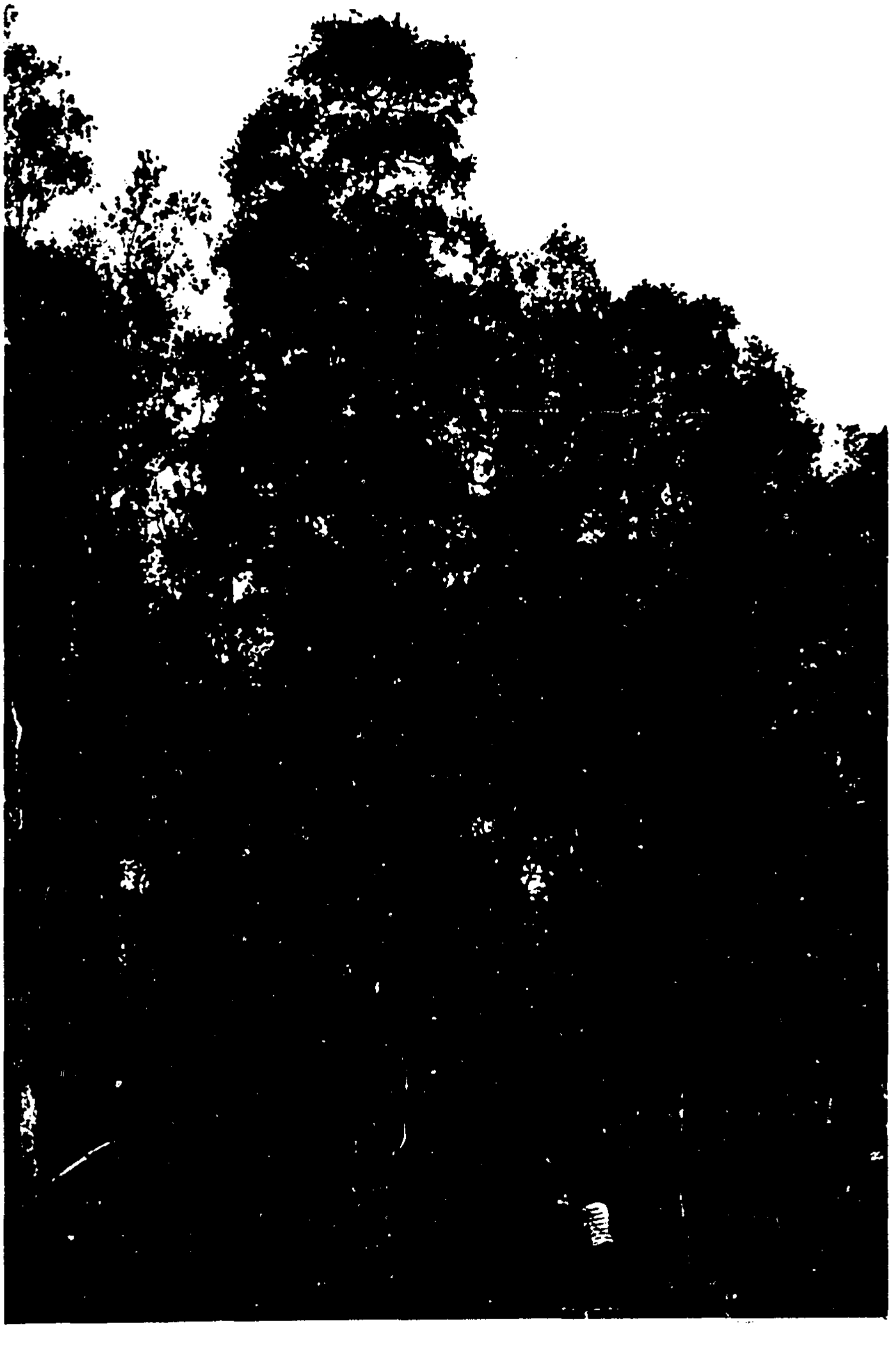
TABLE VII (Continued). VEGETATION STRATIFICATION

Flow	No. of Strata and Major Components	Maximum Height (m)	Mean Heights of Plants in Strata (m)	Mean Depths of Strata (m)	Total Stratum Depth (m)
Upper Stainback	1) Metrosideros	24.8	20.2	14.0	18.0
	2) Cibotium		5.0	4.0	
Lower Stainback	1) Metrosideros	19.0	18.0	12.2	14.6
	2) Coffea, Cibotium		5.5	2.4	
Honaunau	1) Metrosideros	26.6	25.0	8.0	12.0
	2) Cibotium		5.0	4.0	
Prehist. Kapoho	1) Pandanus	12.0	10.7	8.2	11.9
	2) Psidium		5.5	3.7	

TABLE VIII. TREE VOLUME, TREE DENSITY AND CANOPY COVER

Flow	No. Trees Sampled	Mean d.b.h.	Mean Tree Vol. (cubic decim.)	Tree Density (trees/hect.)	Tree Mortality (trees/hect.)	Canopy Cover %		
						Total	Metrosideros	Ferns
1955	10	0.5cm	0.05	-	0	80	>1	>1
1942	47	0.5	0.03	2,750	0	94	>1	0
1881	60	2.3	0.56	3,910	170	66	12	32
1855	35	2.5	0.57	2,920	170	74	28	26
1852	62	3.9	2.85	5,160	330	78	12	48
1840H	10	5.7	21.50	-	-	100	52	48
1840L	20	5.0	19.56	-	0	72	24	>1
1750H	10	63.0	7,544.7	-	-	100	76	12
1750L	10	26.0	1,148.6	-	0	70	10	>1
Upper Stainback	25	29.0	1,420.0	170	0	100	48	48
Lower Stainback	10	27.0	901.4	-	0	100	72	16
Honaunau	25	46.0	4,096.0	-	-	-	-	-
Prehist. Kapoho	10	15.0	194.7	-	-	100	0	0

Figure 9. Metrosideros forest near the Lower Stainback (aa) sampling site, Mauna Loa : 300 ft. elevation. (Cibotium glaucum tree-ferns and the vine Freycinetia arborea can be seen in the understorey).



sampled, the vegetations of the 1942, 1881, 1855, 1852, Honaunau and Upper Stainback flows appear to be stages in this succession (Figs. 10 - 14).

Changes in the age-structure of the Metrosideros population are indicated by change in the height-class of Metrosideros trees with time on later historic flows (Table VI). With increasing time there is a progressive shift of the largest frequency class to taller height classes. Although no Metrosideros seedlings or saplings were seen at the Upper Stainback site, there were a number of resprout shoots from semi-prostrate trunks. Elsewhere on the flow, seedlings of Metrosideros were found occasionally growing on Cibotium trunks.

The succession on pahoehoe flows differs from that on aa in that juvenile Cheirodendron trigynum are more abundant on pahoehoe. If this trend continues, one would expect to find Cheirodendron forming part of the canopy on still older flows but such flows were not found on Mauna Loa or Kilauea.

4. Rockland ⟶ Metrosideros forest ⟶ Metrosideros/Diospyros forest: Stages in this succession were seen only on aa flows below 1000 feet in the Puna rift district. The 1955 site may be an early stage (Fig. 15). The 1750H site (Fig. 16) is a later stage though the Diospyros ferrea is still only an upper understorey species. That Diospyros will ultimately form part of the canopy may be inferred from the absence of Metrosideros juveniles or resprout growth and the presence of juvenile Diospyros of various heights. Dicranopteris, though present, appears to have been less important during intermediate stages than in successions "2" and "3" described above.

Figure 10. Profile diagram of *Metrosideros/Dicranopteris* treeland on the 1855 (pahoehoe) sampling site, Mauna Loa : 3660 ft. elevation. (D = *Dicranopteris linearis*, M = *Metrosideros polymorpha*, Ma = *Machaerina angustifolia*)

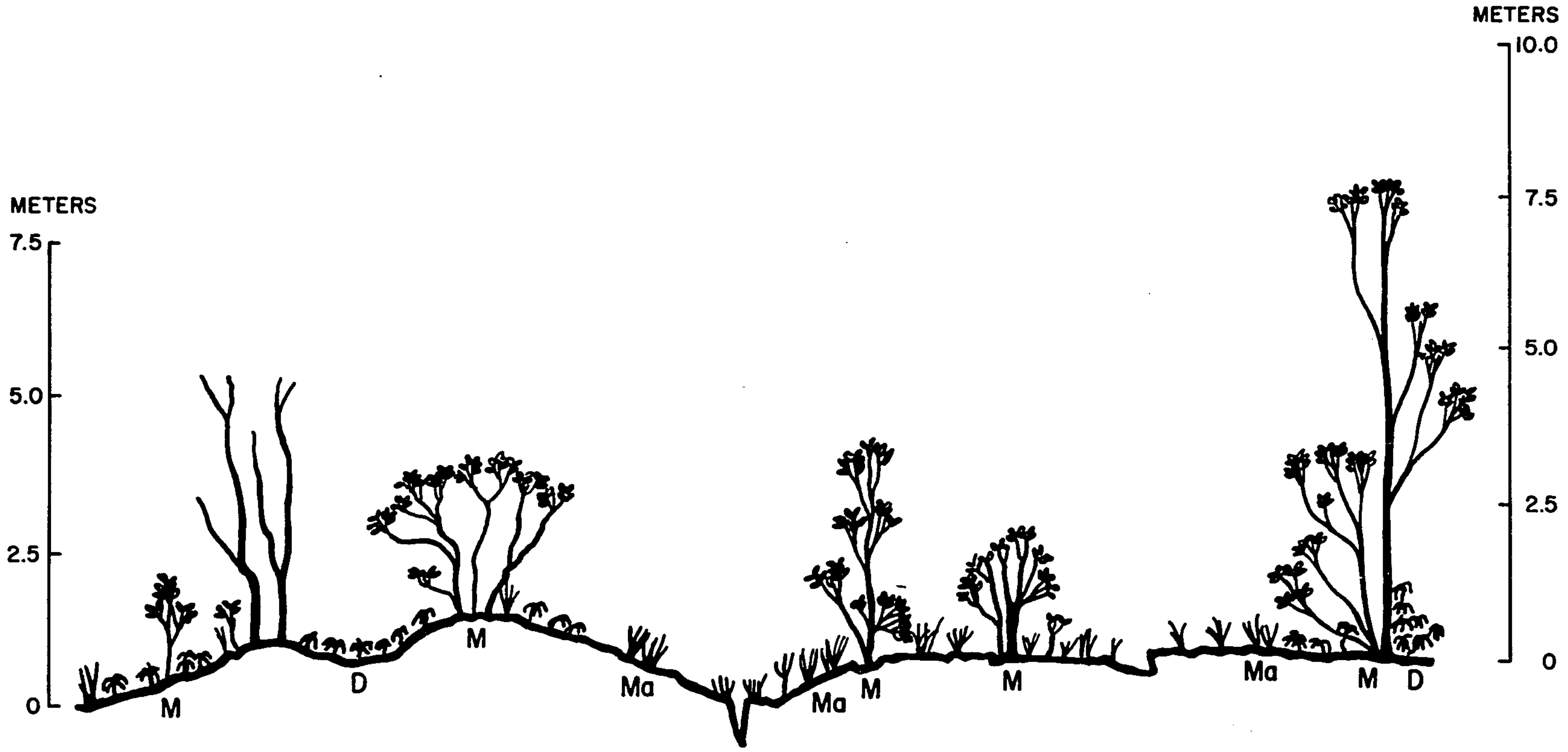

METERS
7.5
5.0
2.5
0
M
D
M
Ma
Ma
M
M
Ma
M
D
METERS
10.0
7.5
5.0
2.5
0

Figure 11. *Metrosideros/Dicranopteris* treeland on the 1855 (pahoehoe) sampling site, Mauna Loa : 3660 ft. elevation. (The abundant sedge growing with the *Dicranopteris* is *Machaerina angustifolia*.)

Figure 12. Profile diagram of *Dicranopteris* fernland on the 1852 (aa) sampling site, Mauna Loa : 3660 ft. elevation.
(D = *Dicranopteris linearis*, L = *Lycopodium cernuum*,
M = *Metrosideros polymorpha*, Ma = *Machaerina angustifolia*,
S = *Sadleria cyatheoides*, V = *Vaccinium calycinum*.)

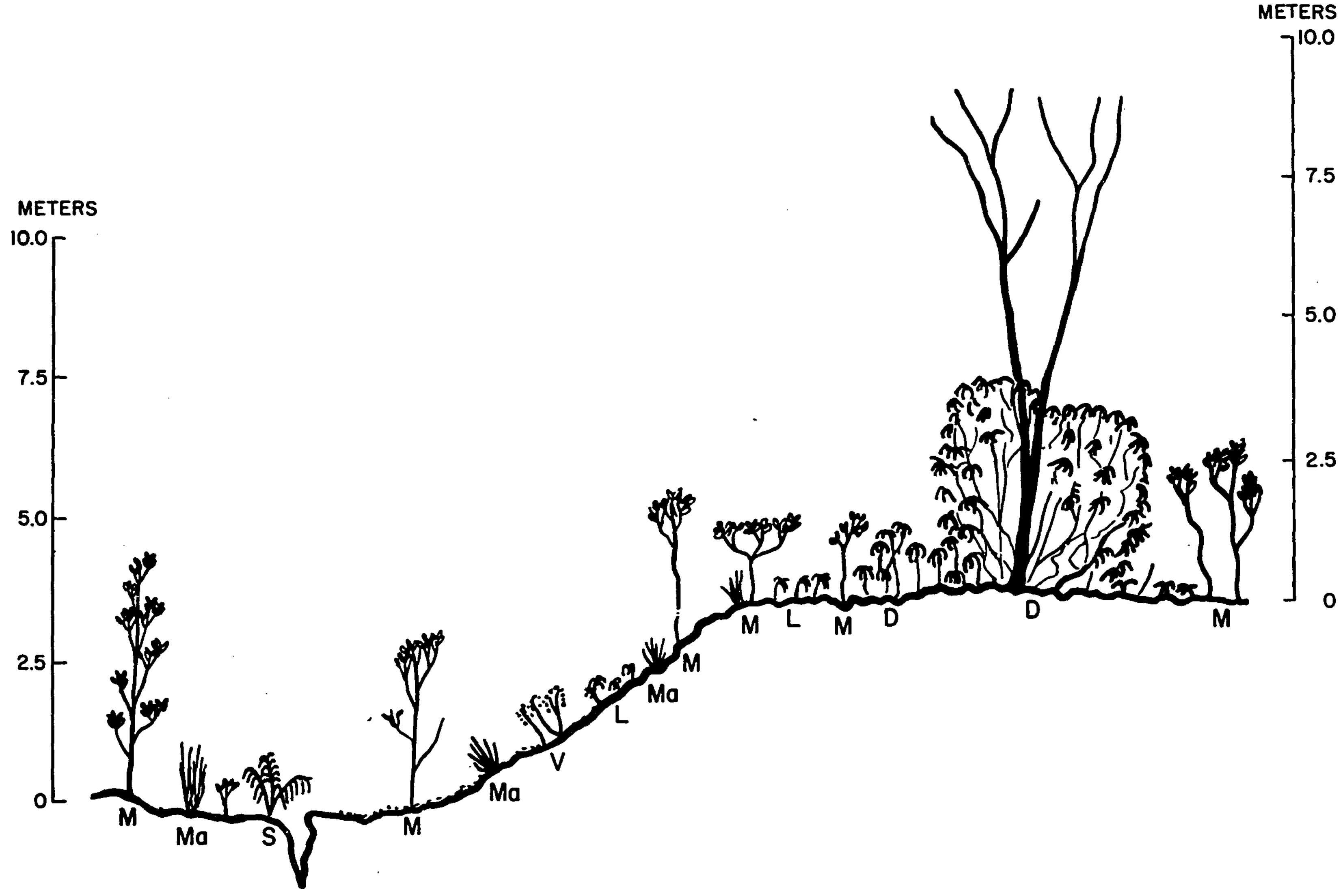

METERS
10.0
7.5
5.0
2.5
0
M
Ma
S
M
Ma
V
L
Ma
M
M
L
M
D
D
M
METERS
10.0
7.5
5.0
2.5
0

Figure 13. *Dicranopteris* fernland on the 1852 (aa) sampling site, Mauna Loa : 3660 ft. elevation.

(The sedge *Machaerina angustifolia* is growing among *Dicranopteris linearis* ferns in the foreground. Trees of *Metrosideros polymorpha* appear in the background).

Figure 14. Profile diagram of <u>Metrosideros/Cibotium</u> forest on the Upper Stainback (aa) sampling site, Mauna Loa : 3780 ft. elevation. (C = <u>Cibotium glaucum</u>, M = <u>Metrosideros polymorpha</u>.)

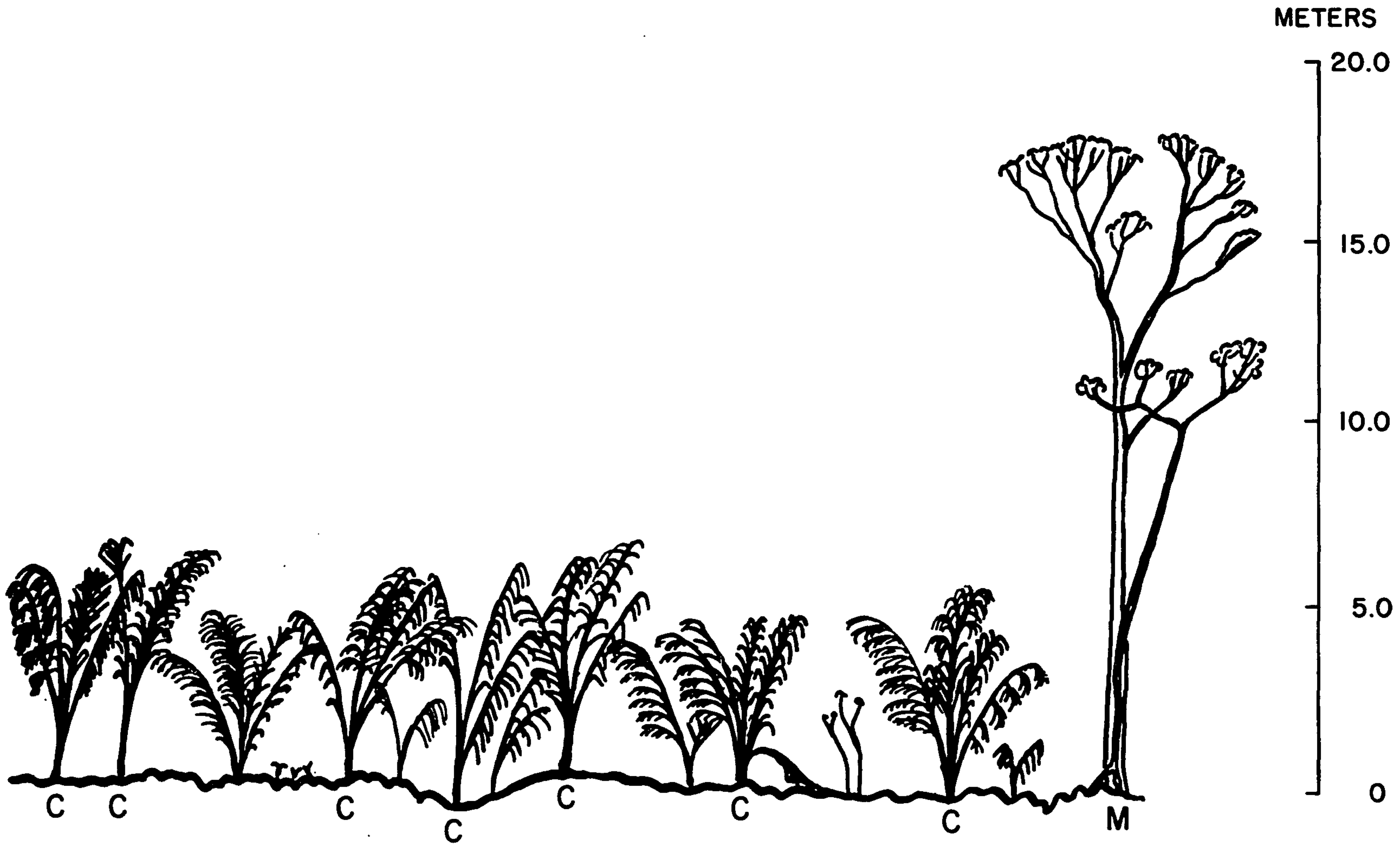
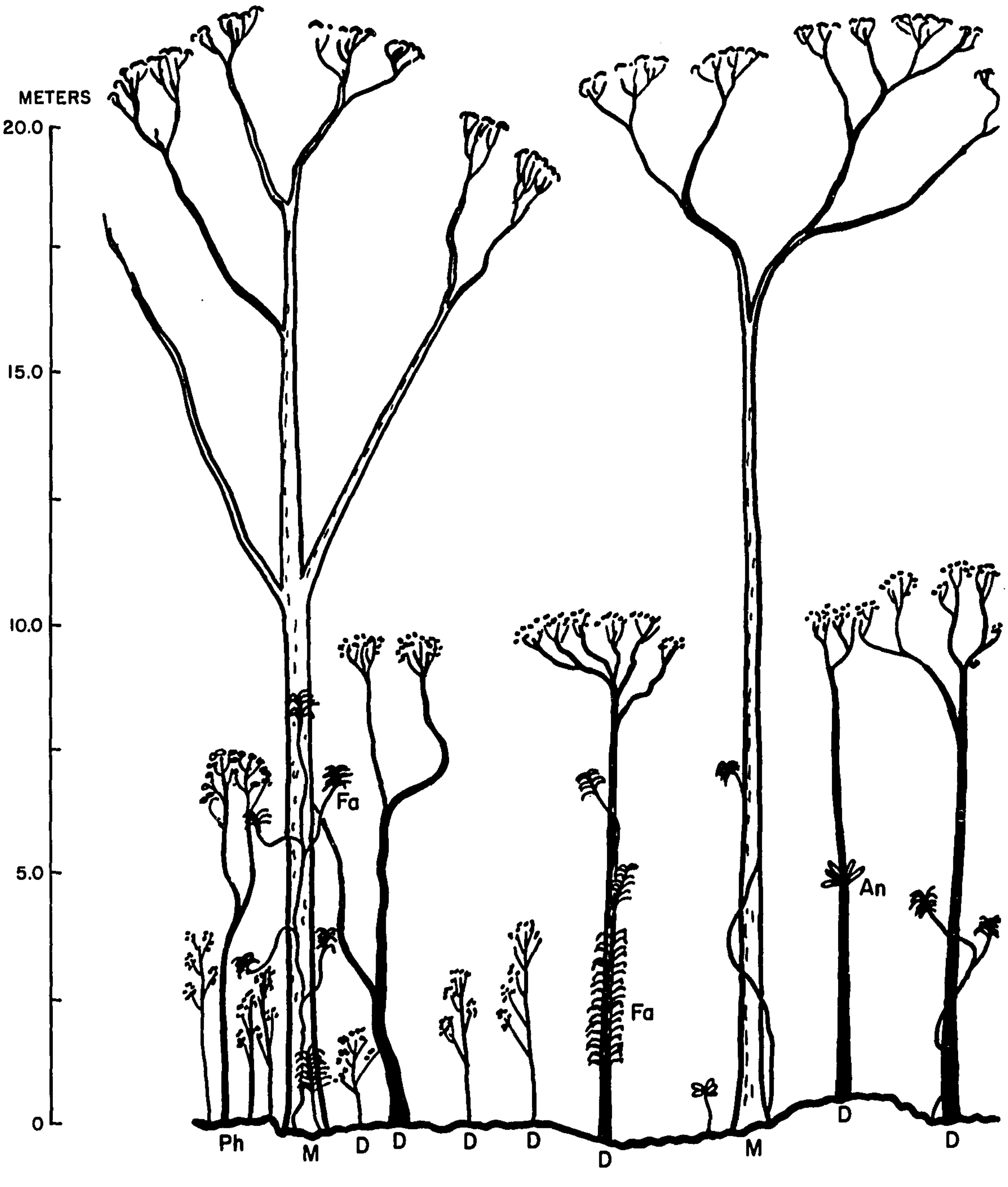

METERS
20.0
15.0
10.0
5.0
0
C
C
C
C
C
C
C
M

Figure 15. *Stereocaulon* lichenfield on the 1955 (aa) sampling site, Kilauea: 930 ft. elevation. (*Metrosideros* forest on prehistoric flow in background.)

Figure 16. Profile diagram of *Metrosideros* forest on the 1750H (aa) sampling site, Kilauea : 990 ft. elevation. (An = *Asplenium nidus*, D = *Diospyros ferrea*, F = *Freycinetia arborea*, M = *Metrosideros polymorpha*, Ph = *Psychotria hawaiiensis*).


METERS
20.0
15.0
10.0
5.0
0
Fa
An
Fa
Ph
M
D
D
D
D
D
M
D
D

No Diospyros was observed on the 1750L site but Doty and Mueller-Dombois (1966) record this species from prehistoric flows at similar altitudes near the 1955 Kii flow. Summer-dry periods are more frequent on the 1750L site than elsewhere in the study area.

Trends in numbers of species and stratification: There are no obvious trends in numbers of species (Table V) apart from the fact of fewer species during the earliest stages of development.

Two main strata ($>$ 0.5m) appear within 100 years of flow formation but there appears to be no further increase in the number of strata on older flows. In general, total stratum depth increases with age although the 1840L site is exceptional. This site has the highest mean annual temperature among the historic flows and it is considered that the increased evaporation may result in dry periods long enough to restrict growth.

Age Parameters

Table VIII lists the parameters that were considered for age indices. Tree density varies widely: at first increasing while Metrosideros plants are still able to establish, then decreasing while natural thinning occurs. Thus density is not a single-valued function of time. Each of the parameters: mean trunk diameter (d.b.h.) of all trees sampled, mean d.b.h. of the largest 10 trees, and mean tree volumes, were plotted against time. It is clear that with increasing time and reduction of growth rates, these parameters approach asymptotic values. Cover is very variable depending on local site conditions. Thus none of the vegetation parameters examined appears to be useful in aging a lava-flow ecosystem.

Growth Rings

It was considered that Metrosideros trees growing at cooler elevations might show annual rings and thus allow one to age some of the undated flows. Two older trees, one from the 1881 flow at 5000 feet and the other from the 1852 flow at 3600 feet were selected as probably having established within a few years of lava-flow formation. Sections were cut and polished on a sanding machine before examination with a low-power binocular microscope. A number of rings were difficult to distinguish but in both cases the number counted was less than the age of the flow (1881: 37 rings and 1852: 70 rings).

There is probably a better chance of finding annual rings in trees growing in lower rainfall areas, particularly those places where there are marked periods of summer drought.

Soil Horizon Development

Soil horizon development on the lava flows sampled is almost completely restricted to a surficial layer of organic matter. Table IX gives the depth of this layer for the different sites as well as some factors of climate and vegetation that influence the development of this horizon. With the most recent historic flows there is virtually no profile differentiation. As age increases, the organic matter deepens and penetrates the interstices of the stones and boulders. Apart from differences related to age, there is a marked difference in organic horizon depths between low altitudes ($<$ 1000 ft.) and middle altitudes (3600 - 3800 ft.). This is probably an effect of the higher temperatures at lower altitudes in increasing the rate of organic matter decomposition (cf Jenny 1931). The very shallow organic matter depth of the Lower

TABLE IX. DEPTH OF ORGANIC HORIZON AND SITE FACTORS

Flow	Altitude (ft.)	Mean Ann. Rainfall (in.)	Mean Ann. Temp. (°F.)	Total Veg. Stratum Depth (m)	Depth of Organic Horizon (cm)	
					Mean	S.D.
1955	930	100	69.9	0.3	0.0	-
1942	3720	150	60.2	0.4	0.2	-
1881	3800	220	59.9	2.2	1.0	0.9
1855	3660	250	60.4	2.3	5.0	5.0
1852	3660	210	60.4	3.2	11.9	12.0
1840H	650	130	70.9	6.0	0.8	0.4
1840L	40	115	73.1	3.0	0.5	0.5
1750H	990	110	69.7	16.7	1.7	0.4
1750L	300	90	72.1	10.0	1.5	0.4
Upper Stainback	3780	140	60.0	18.0	16.5	9.7
Lower Stainback	300	140	72.1	14.6	0.5	-
Prehist. Kapoho	90	105	72.9	11.9	1.0	0.8

Stainback site cannot be attributed to fires or other disturbances that have occurred here in the past; Jenny et al (1949) found that a near-equilibrium in the accumulation of organic matter was reached in less than 10 years in tropical forest. The data of Table IX show that, even allowing for temperature differences, there is no close relationship between organic horizon depth and the total depth of vegetation strata.

Two representative profiles are described below:

(i) 1852 site, Mauna Loa: 3660 ft. Profile under *Metrosideros* (8 m) and *Dicranopteris* (3 m).

4-0 cm	loose *Dicranopteris* litter with mosses.
0-10cm	black (5YR 2/1) humus; about 75% fine roots, densely matted; very fine granular structure, abrupt boundary,
on	aa stones (5 - 50 cm diam.) with thin black colloidal coating; interstices between boulders partially filled with black (5YR 2/1) humus; slightly sticky; weakly developed very fine granular structure; abundant fine roots, earthworms present. Humic material decreases in amount with depth.

(ii) Upper Stainback site, Mauna Loa : 3780 ft. Profile under *Metrosideros* (18 m) and *Cibotium* tree-fern (4 m).

5-0 cm	loose *Cibotium* and *Metrosideros* litter.
0-3 cm	mat of fine and coarse roots overlying and separate from:
3-15cm	dark reddish brown (5YR 2/2) humus; about 25% fine roots; nonsticky; moderately developed fine

granular structure; abrupt boundary,

on aa stones (5 - 45 cm diam.) with reddish brown colloidal coatings; dark reddish brown humus in rock interstices; nonsticky; moderate to strongly developed medium granular structure; abundant fine roots. Humic material paler (5YR 3/2) with increasing depth.

Humic material on the two pahoehoe flows examined (1881 and 1855) was black (7.5 YR 2/0), nonsticky and structureless. Except near fissures, it was evident that waterlogging of the organic horizon was of much more frequent occurrence than on neighboring aa flows. This can be related to the relatively impervious pahoehoe surface beneath.

pH Changes

Rock pH

The results of the rock pH measurements are summarized in Table X. The small Δ pH (pH_{KCl} - pH_{H_2O}) values of the 'unweathered' (U) samples from the 1852, 1840H and 1840L sites, indicate that the original value for an unweathered rock at time zero may be very close to 0.0. A sample of unweathered lava collected by Dr. G.A. Macdonald from the 1899 flow in a high-altitude, low-rainfall zone of Mauna Loa gave a ΔpH value of -0.05. The Δ pH values of the U samples from the 1750H and Upper Stainback sites suggest that these rocks may be slightly weathered.

The possibility that ΔpH values indicate the development of charged surfaces in the weathering rock was investigated by making duplicate measurements of C.E.C. in two samples: one from the 1840L site (ΔpH = -0.26) and one from the Upper Stainback (ΔpH = -1.07). There was no

TABLE X. pH MEASUREMENTS

Lava Flow	pH_{H_2O}						Δ pH (pH_{KCl} - pH_{H_2O})						pHc *	
	Unweathered			Weathered			Unweathered			Weathered				
	No.	Mean	S.D.	No.	Mean	S.D.	No.	Mean	S.D.	No.	Mean	S.D.	Mean	S.D.
1955	10	9.43	0.11	10	8.07	0.33	-	-	-	10	-0.40	0.08	1.77	0.38
1942	10	9.40	0.08	10	8.33	0.45	-	-	-	10	-0.22	0.14	1.28	0.57
1852	10	9.55	0.09	10	7.84	0.33	10	0.02	0.08	10	-0.37	0.13	2.07	0.42
1840H	8	9.20	0.27	10	7.96	0.29	8	0.02	0.09	10	-0.56	0.09	1.80	0.36
1840L	10	9.36	0.14	10	8.55	0.35	10	-0.01	0.11	10	-0.17	0.11	0.98	0.47
1750H	10	9.02	0.12	10	7.10	0.29	10	-0.20	0.10	10	-0.61	0.07	2.92	0.28
1750L	6	9.41	0.07	6	7.40	0.18	-	-	-	6	-0.61	0.07	2.62	0.25
Upper Stainback	10	9.37	0.14	4	6.79	0.23	10	-0.36	0.12	4	-0.84	0.12	3.41	0.25
Lower Stainback	5	9.35	0.05	5	6.50	0.29	-	-	-	5	-0.67	0.07	3.52	0.30
Prehistoric Kapoho	5	9.18	0.09	5	7.17	0.53	-	-	-	5	-0.64	0.09	2.66	0.58
Honaunau	3	9.49	0.08	3	6.94	0.39	-	-	-	3	-0.64	0.04	3.19	0.41
1855	5	9.33	0.22	5	7.29	0.35	-	-	-	5	-0.84	0.08	2.89	0.44
Savaii 1760	5	9.57	0.16	5	9.30	0.29	-	-	-	5	-0.82	0.09	1.09	0.23
Prehistoric Upolu	5	9.70	0.03	5	7.24	0.26	-	-	-	5	-1.02	0.09	3.48	0.46

Accuracy: ± 0.025 pH units. Precision: ± 0.030 pH units. * See p. 95.

measurable C.E.C. in either case suggesting that the ΔpH measurements are not reflecting charge density but rather differences in the solubility of rock constituents. Apparently solubility changes with weathering.

All differences between pH_{H_2O} values for unweathered and weathered rocks are significant at the 99% level of probability. The difference in pH_{H_2O} measurements between U and W samples in any one flow appears to be a useful index of weathering, indicating the extent to which the rock has been leached of bases. The average pH_{H_2O} value for all the dated U rocks from aa flows (excepting 1750H, see below) is 9.39, that for the undated aa flows is 9.35, and for the two Samoan pahoehoe flows is 9.63. The value for the 1750H site (9.02) looks rather low by comparison and suggests again that the U rocks from this site are in fact somewhat weathered. The value of 9.41 for the 1750L site (same flow) appears to be nearer the true value. This figure was used for the 1750H site in calculating the pH change value, discussed below.

The pH change (henceforth referred to as pHc) is another useful index of weathering calculated from the mean difference between pH_{H_2O} of the U rocks and pH_{KCl} of the W rocks (Table X), i.e.

$$pHc = \frac{\Sigma\,(pH_{H_2O} \text{ of U rocks})}{n} - \frac{\Sigma\,(pH_{KCl} \text{ of W rocks})}{n}$$

where n = number of rock samples measured.

This parameter was found to have a higher correlation coefficient with time (0.58) than other pH measurements (see Appendix IV) and proved to be a useful index of age.

Litter pH

Litter pH measurements for each of the major species occurring on the sites sampled were made in order to characterize the effects of major species on soil development (see discussion under "Effective Plant Factor").

Species	No. of Samples	pH
Metrosideros polymorpha	4	4.32
Dicranopteris linearis	2	4.05
Cibotium sp.	2	3.82
Pandanus tectorius	4	7.10

Sherman and Kanehiro (1948) reported values of 3.9 and 3.8 for the leaf moulds of *Metrosideros* and *Dicranopteris* respectively.

Hydration Changes

Weight-Loss Measurements

The 110 - 350° C. weight-loss measurements (Table XI) were made in order to measure the amount of water gained by hydration and hydrolysis of primary minerals during weathering. The weight-loss measured in this way includes both hydroxyl water and adsorbed water. Kelley et al. (1936) working with minerals and soil colloids, found that most of the loss below 400° C. was adsorbed water. However, they found that OH ions bought to the surface with grinding were released at lower temperatures.

The precision given is for the weathered rocks only. With the very small weight-losses of some of the unweathered rocks the percentage precision for duplicate measurements was usually high and occasionally exceeded 100%. It may be noted also that the standard deviation for different unweathered samples from the same flow, sometimes exceeded the mean.

TABLE XI. 110 - 350° C. WEIGHT-LOSS MEASUREMENTS
(Percentages of 110° C. wt.)

Flow	Unweathered			Weathered		
	No.	Mean	S.D.	No.	Mean	S.D.
1955	10	+0.05	0.07	10	0.80	0.20
1942	10	0.06	0.05	10	0.78	0.36
1852	10	0.06	0.06	10	0.94	0.65
1840H	8	0.25	0.09	10	1.21	0.20
1840L	10	0.03	0.04	6	0.75	0.28
1750H	10	0.20	0.08	6	2.03	0.45
1750L	6	0,03	0.08	6	2.15	0.45
Upper Stainback	10	0.09	0.02	4	3.28	0.44
Lower Stainback	5	0.24	0.04	5	2.87	0.81
Prehistoric Kapoho	5	0.17	0.01	5	1.97	0.61
Honaunau	3	0.17	0.05	3	2.41	0.57
1855	5	0.11	0.02	5	0.93	0.27
Savaii 1760	3	0.22	0.02	3	0.44	0.03
Prehistoric Upolu	5	0.05	0.04	5	1.66	0.33

Precision: 0.11 ± 0.09% (9 determinations)

All differences between U and W rocks were significant at the 99% level of probability. The weight losses for the U rocks of dated flows averaged 0.13% and it seems likely that the value for a sample of newly formed lava would be less than 0.05%. With this assumption, the weight losses for the W rocks can be taken as an index of weathering on basalt flows without correction for differences between flows at time zero of soil formation. This parameter gave the highest correlation coefficient with time (0.68) of any parameter measured and proved to be a useful age index (see Appendix IV).

Comparing the values for U rocks between the two 1840 sites and between the two 1750 sites it seems probable that the U rocks of the 1840H and 1750H sites are slightly weathered. Both the H sites are in cooler, higher rainfall areas than the L sites.

Rehydration Measurements

Weight gains on rehydration at 50, 79 and 98% relative humidities were small. The mean weight gains expressed as percentages of the 350° C. rock weight are shown below. All samples are from the 1852 site.

Relative Humidity	U Rocks (2 samples)	W Rocks (4 samples)
50%	0.07%	0.12%
79	0.14	0.21
98	0.16	0.46

Other rehydration weight-gains measured on two groups of 6 samples ranged between 0.1% (50% R.H.) and 0.98% (98% R.H.) for the 1942 flow, and 0.08 (50% R.H.) to 0.43% (98% R.H.) for the Upper Stainback flow. Since variability was high and there appeared to be little relation to age of rock, these measurements were not made on other flows.

Hydration-rinds

Thin sections were prepared of lava droplets from the 1840, 1793 and 1750 flows of Kilauea and from the Lower Stainback flow of Mauna Loa. Microscopic examination with normal viewing and cross niccols showed a micro-crystalline structure with only isolated small areas of interstitial glass. Other sections of scoriaceous material were examined in which a glassy matrix was present but there was insufficient glass at the rock surface for any hydration-rind to be seen. This method of aging appears unsuitable for basalt flows.

Oxidation Changes

$\Delta\, mV_t$ values were obtained by subtracting the potential at the varied time intervals of measurement from the potential at the beginning of the experiment (Bardossy and Bod 1961). $\Delta\, mV_t$ values were measured in the range -58 mv to +269 mv with samples from three flows, but there was no relationship with age. The above authors used the potential differences between experiments with different concentrations of oxidising agent as a quantitative index of the oxidation state of the rock ($\Delta\, mV_1$ values). Values of -80 to -341 mv were measured in the present study but again there was no relationship to age.

Reference to Appendix I shows that the ferrous/ferric ion ratio can vary widely from about 10:1 (1840 flow) to almost 1:1 (1942 flow) with associated large differences in the quantity of ferrous ion. Ferrous ion content is probably the chief variable affecting the oxidation potential of the rock. Differences in ferrous ion content between the flows examined may be obscuring differences in the oxidation state that have resulted from weathering.

Mineralogical Changes

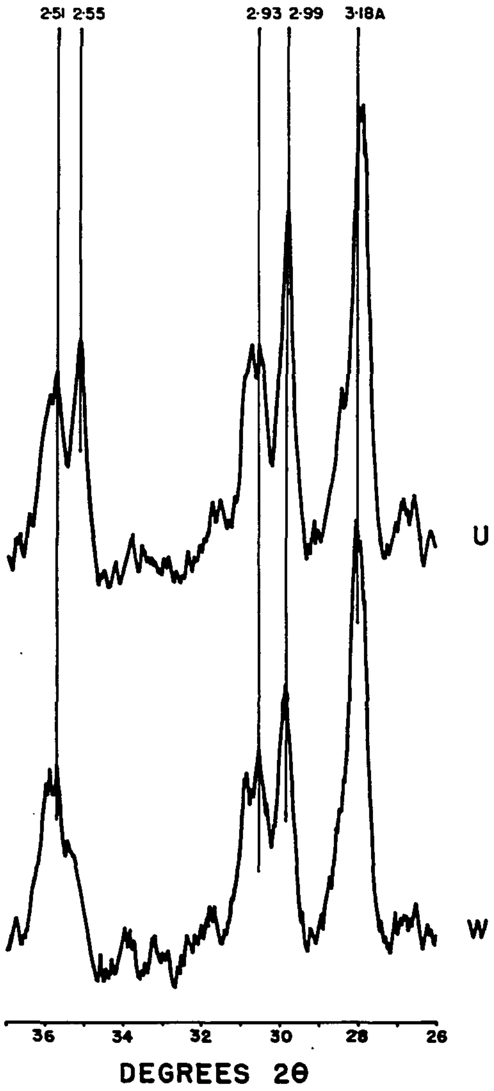
Felspars and Pyroxenes

Figures 17 - 19 are examples of the powder diffraction patterns obtained with samples from three aa flows (1942, 1852 and Upper Stainback) and two pahoehoe flows (1881 and 1855). Table XII gives the three strongest X-ray reflections for common basaltic minerals (Smith 1960) and the wavelengths of the strongest peaks found in the powder samples examined.

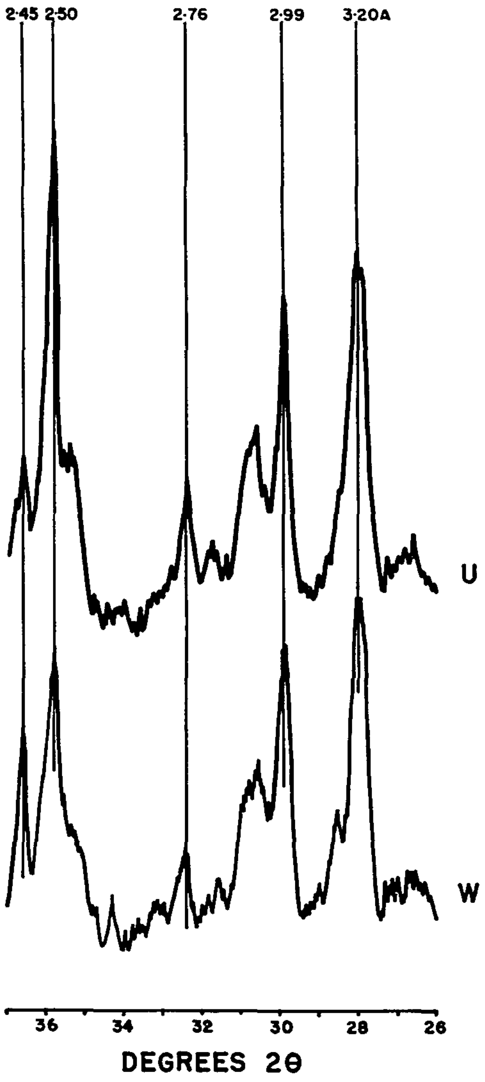
The most clearly defined and consistently occurring peaks are at: 3.18 - 3.20A (interpreted as plagioclase felspars and hypersthene), 2.99A (clinopyroxenes such as pigeonite and augite), 2.90 - 2.92A (lower intensity peak for hypersthene with other unidentified minerals) and 2.51A (iron oxides and olivine). Clearly defined peaks for forsterite appeared only in patterns from the olivine-rich 1852 and Stainback aa flows, and in the 1855 pahoehoe flow. Although these interpretations are by no means unequivocal, Macdonald and Katsura (1964) found either pigeonite, hypersthene or both minerals in coarse-grained tholeiitic rocks. Augite was usually present as well. They were not able to identify the groundmass pyroxenes in fine-grained rocks.

Differences in particle size, packing and preferred orientation prevent a quantitative comparison of mineral composition between flows. This difficulty can be overcome to some extent by working with internal ratios of minerals and the differences in these ratios between samples. Table XIII lists values for plagioclase / pigeonite and pigeonite / 'hypersthene' ratios based on measurements from diffraction patterns. Since the hypersthene identification is uncertain, this measurement is best

Figure 17. X-ray powder patterns of 1942 (left) and 1852 (right) aa samples. (U = unweathered and W = weathered rocks)

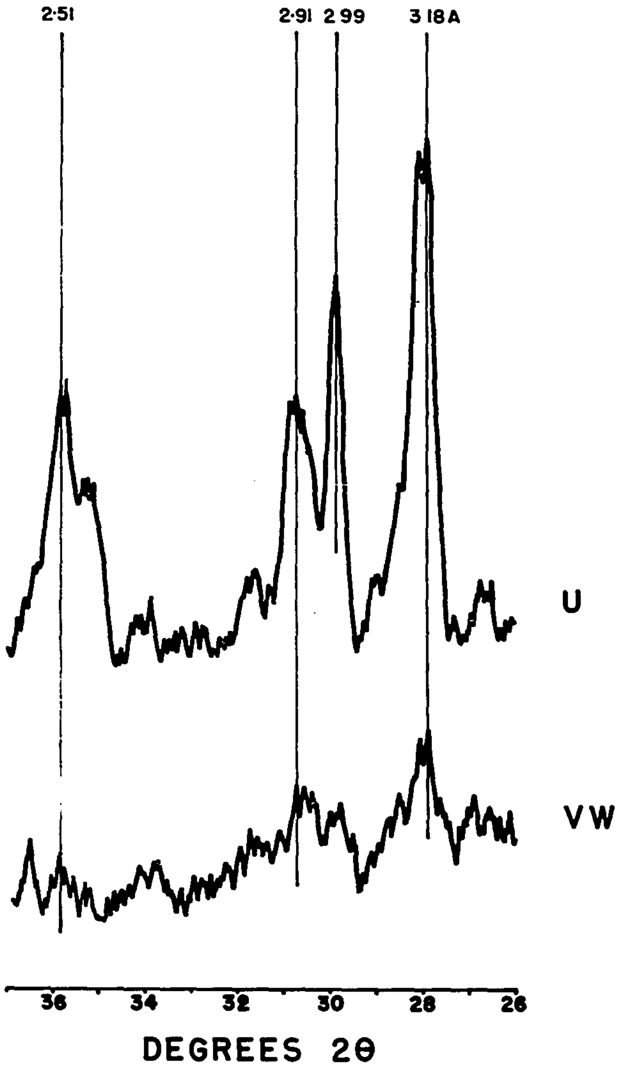


2·51
2·55
2·93
2·99
3·18A
U
W
36
34
32
30
28
26
DEGREES 2θ



2·45
2·50
2·76
2·99
3·20A
U
W
36
34
32
30
28
26
DEGREES 2θ

Figure 18. X-ray powder patterns of 1881 (left) and 1855 (right) pahoehoe samples. (U = unweathered and W = weathered rocks)


2·51
2·91
2 99
3 18A
U
VW
36
34
32
30
28
26
DEGREES 2θ

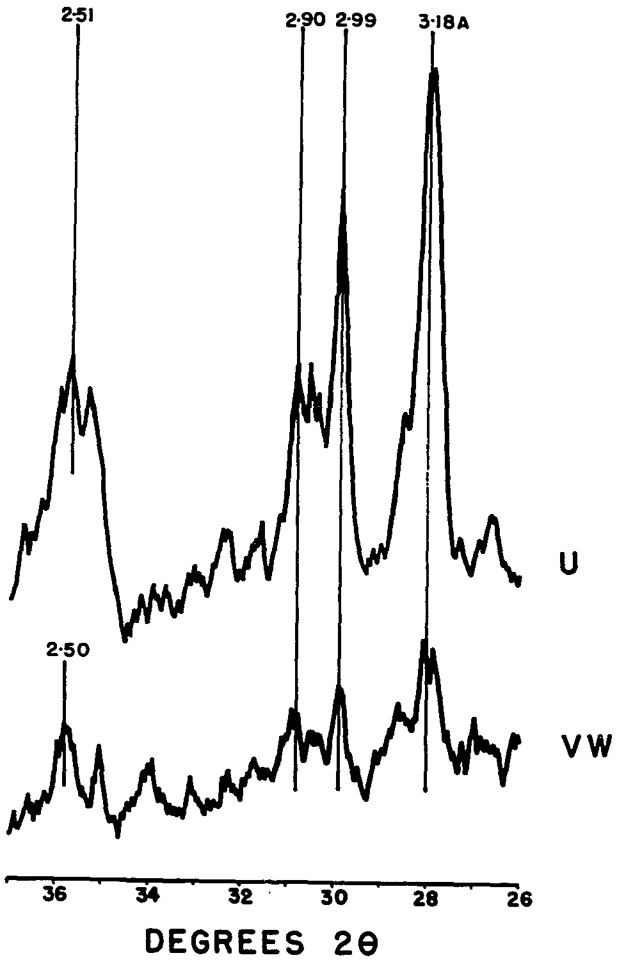

2·51
2·90
2·99
3·18A
U
2·50
VW
36
34
32
30
28
26
DEGREES 2θ

Figure 19. X-ray powder patterns of Upper Stainback aa samples. (U = unweathered and W = weathered rocks)

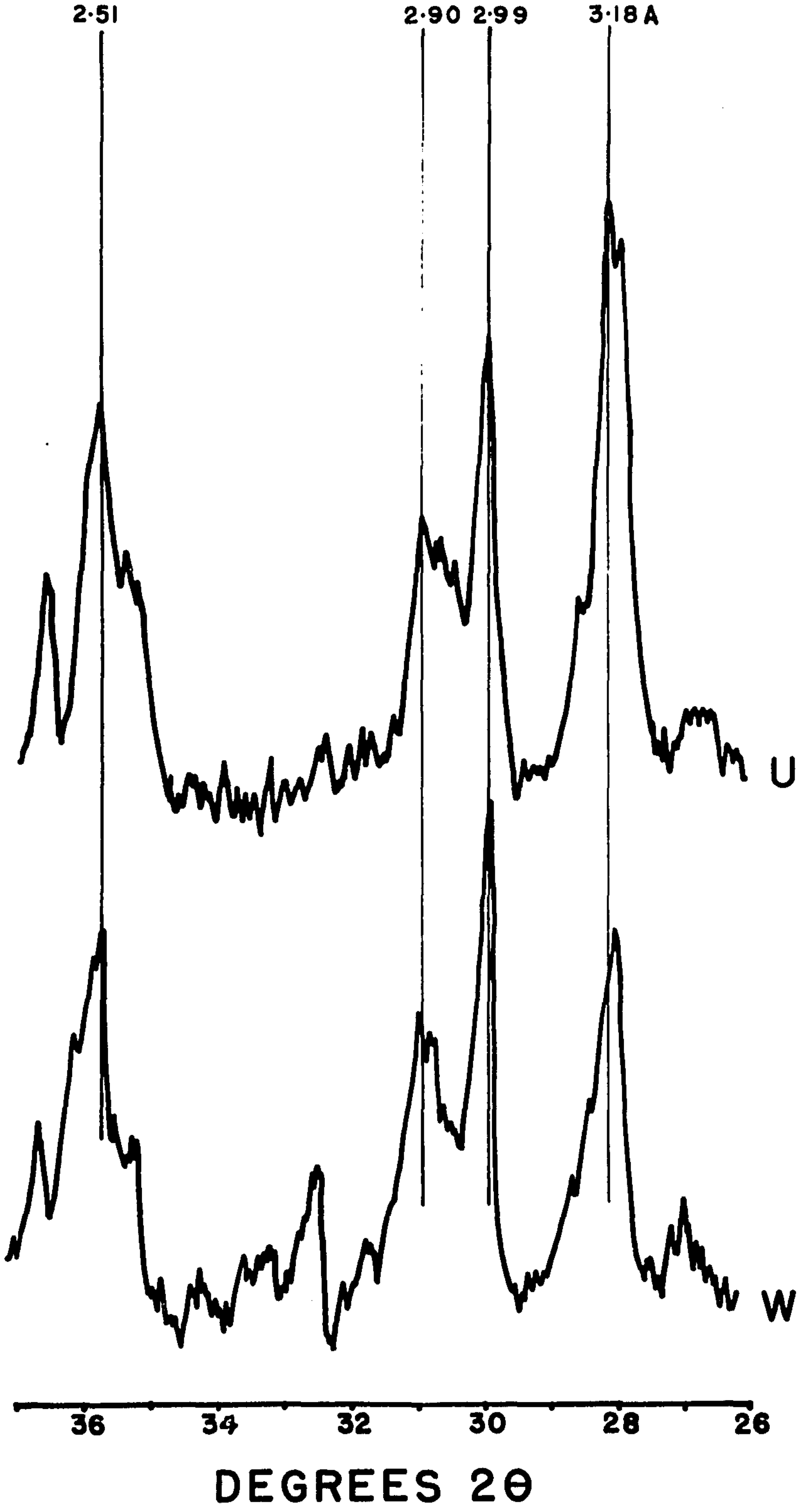

2·51
2·90
2·99
3·18 A
U
W
36
34
32
30
28
26
DEGREES 2θ

TABLE XII. DIFFRACTION PEAKS FOR STANDARD MINERALS AND MINERALS FOUND IN HAWAIIAN ROCKS

Mineral	Diffraction peaks (A) in Order of Intensity			Diffraction Peaks Found in Hawaiian Samples	Interpretation
Labradorite	3.20	3.18	4.04		
	3.20	4.07	2.53	3.18-3.20	Plagioclase felspars and hypersthene
Hypersthene	3.20	2.89	1.49		
Augite	2.99	1.62	1.43	2.99	Clinopyroxene, e.g. pigeonite, augite
				2.89, 2.90-2.92	Hypersthene and unidentified minerals
Fayalite	2.83	2.50	2.57		
	2.82	2.50	1.78		
Forsterite	2.77	2.52	3.89		
	2.77	2.51	2.46	2.76-2.77	Olivine
	2.77	3.88	2.51		
Ilmenite	2.74	1.72	2.54		
Hematite	2.69	2.51	1.69		
Magnetite	2.53	1.48	2.97	2.54-2.55	Titanomagnetite
Maghemite	2.51	1.47	2.95	2.51	Titanomaghemite
				2.44 2.44-2.46	?

TABLE XIII. PLAGIOCLASE/PIGEONITE AND PIGEONITE/HYPERSTHENE RATIOS

Flow		Plagioclase/Pigeonite				Pigeonite/'Hypersthene'			
		No.	Peak Heights* Plag.	Pign.	Ratio	No.	Peak Height Hyper.	Ratio	W Ratio / U Ratio
1942 (aa)	U	4	59.0	42.0	1.40	3	25.5	1.65	0.88
"	W	4	56.5	37.5	1.51	3	25.8	1.45	
1852 (aa)	U	4	43.0	39.5	1.09	4	22.0	1.80	0.98
"	W	4	41.0	36.0	1.14	2	20.5	1.76	
Upper Stainback (aa)	U	4	43.0	36.5	1.18	4	22.0	1.66	1.11
"	W	4	29.5	42.5	0.69	4	23.0	1.85	
1881 (pahoehoe)	U	2	55.3	39.0	1.42	2	25.0	1.56	0.88
"	VW	2	15.8	11.0	1.44	2	8.0	1.38	
1855 (pahoehoe)	U	2	57.8	45.0	1.28	2	27.0	1.67	1.90
"	VW	2	18.5	19.0	0.97	2	6.0	3.17	

*Arbitrary units.

treated simply as a 2.90 - 2.92A peak. The three aa flows chosen give an indication of the weathering trend that occurs in a high-rainfall zone between 3000 and 4000 feet elevation. These flows all have similar mean annual temperatures (c. 60° F.) and occur in rainfalls varying from 140 to 210 inches.

The changes in the plagioclase/pigeonite ratios between unweathered and weathered rocks of the aa flows, suggest that the rate of weathering of pigeonite is at first more rapid than that of plagioclases, but with increasing time the plagioclases are lost more rapidly. The very weathered (VW) samples are surface glassy crusts of pahoehoe (p. 35). The losses of all minerals between U and VW rocks (Fig. 18) are so great that little significance can be attached to the differences in plagioclase/pigeonite ratios.

The change in pigeonite/'hypersthene' ratios between weathered and unweathered rocks (also expressed as a ratio in Table XIII) shows an increase with time. It is difficult to interpret this in terms of absolute changes of the two minerals represented. However, the more weathered conditions of the glassy pahoehoe crusts is again evident.

Further work on this aspect was not attempted because of the difficulty of quantifying the changes observed.

Oxide Minerals

No peaks corresponding to the first-order reflections for ilmenite were recorded. The 2.51 - 2.55A group of X-ray peaks, believed to include oxides such as titanomagnetite and titanomaghemite, usually showed changes in shape and numbers of peaks between weathered and unweathered samples (Figs. 17 - 19). In all samples there was a rise in the background intensity of radiation from unweathered to weathered rocks. This change increases with age of flow and degree of weathering. It can be taken as a measure of the concentration of iron that has taken place, particularly on crystal surfaces, which is causing increased scatter of copper radiation from the target tube.

Since titanomaghemite in soils is largely an oxidation product formed during weathering from titanomagnetite (Matsusaka, Sherman and Swindale 1964), an endeavor was made to determine relative amounts of these two minerals. The three most intense diffraction peaks for magnetite occur at 2.53, 1.48 and 2.97A and the corresponding figures for maghemite are 2.51, 1.47 and 2.96A (Rooksby 1961). The equivalent peaks for titanomagnetite and titanomaghemite differ from these values slightly depending on the degree of substitution by titanium and other minerals.

X-ray diffraction patterns of samples from the 1852 and Upper Stainback flows examined with iron radiation failed to show distinguishable titanomagnetite and titanomaghemite peaks. The most intense reflections of these minerals appear to be mixed with diffraction peaks of olivine. Other iron oxide peaks were too small to distinguish.

Two samples from the Upper Stainback flow, one unweathered and one weathered, were examined using the magnetic susceptibility machine. The heating and cooling curves obtained showed some differences but the amount of magnetic minerals was too small to allow reliable measurements. A difficulty with this method is that other minerals can contribute to the magnetic susceptibility so that a true measure of the magnetite-maghemite ratio is not possible.

Separation of the magnetic fraction using a hand magnet was done with some samples. The possibility of using heavy liquids such as Clerici solution for separating the heavy minerals was also considered. The magnetic fraction separated by magnet was too small for analytical purposes. Since the glass content included with the magnetite is variable and dilutes the magnetic fraction separated, this approach was discontinued.

Elemental Changes

Silicon and Aluminum

The results for these determinations are given in Table XIV. Accuracy can be gauged by comparing the values obtained for unweathered rocks with published analyses of previously collected samples from different parts of the flow (Appendix I). The 1852 silica results show close agreement but those for the 1942 flow average 2.6% of SiO_2 less than the published figure. With alumina, the measurements obtained are 1 - 2% of Al_2O_3 lower than the figures published. Thus these results can be used to compare the flows sampled but not as measures of the total silicon and aluminum present.

The silica measured in the 'unweathered' 1750 samples is considerably lower than the average for other unweathered rocks suggesting, in accordance with earlier evidence (see pH and weight-loss measurements), that these rocks are weathered.

The 'unweathered' samples from the Upper Stainback flow are from the centers of 30 - 60 cm diameter boulders about 45 cm below the surface. Other analyses (sodium and calcium, not reported) showed that these samples were more weathered than later samples collected from the centers of large boulders split during recent road construction. These later

TABLE XIV. CHANGES IN TOTAL SILICON (SiO_2) AND ALUMINUM (Al_2O_3)

Element as Oxide	Flow	Unweathered			Weathered			P	% Change
		No.	Mean%	S.D.	No.	Mean%	S.D.		
SiO_2	1942	3	49.46	2.54	3	46.70	3.90	N.S.	-
"	1852	4	48.18	1.59	5	46.68	1.70	< 0.05	-3.1
"	1750*	6	40.05	1.70	6	41.24	2.34	< 0.05	+3.0
"	Upper Stainback*	3	47.52	1.55	4	42.89	3.07	< 0.01	-9.8
Al_2O_3	1942	3	11.48	0.31	3	11.09	0.74	N.S.	-
"	1852	3	9.43	0.98	3	8.06	0.23	< 0.01	-14.5
"	Upper Stainback*	3	9.32	1.70	3	9.79	0.59	N.S.	-

*Unweathered samples from these flows are partially weathered.

Precision for SiO_2 = 0.74 ± 0.46% (6 determinations)

Precision for Al_2O_3 = 0.72 ± 0.31% (4 determinations) samples were used as an unweathered baseline for all subsequent analyses but silicon and aluminum determinations were not made. Thus the loss of silicon and concentration of aluminum on the Upper Stainback flow are almost certainly greater than the measurements reported in Table XV.

The difficulty of getting an unweathered sample together with the rather large sample variability halted further work on silicon as a possible age index. Neither does aluminum appear suitable because of the apparent reversal in the direction of its change: a loss in the 1852 flow followed by what is probably an incipient gain in the Upper Stainback.

Calcium and Sodium

Total calcium and sodium analyses are summarized as oxide percentages in Tables XV and XVI. The results of analyses of unweathered rocks from the 1955, 1942, 1852 and 1840 flows are similar to previously published analyses which are shown in Appendix I.

The results from the Honaunau flow show a rather high calcium figure and this, together with the high standard deviation, make this measurement suspect.

In general it appears that sodium is being lost at more than twice the rate of calcium. This may make sodium a more useful index of weathering, and thus age, during the first two or three hundred years of development, but for older flows calcium may be more useful.

Potassium and Magnesium

The potassium and magnesium changes measured are summarized in Table XVII. The concentration of magnesium with weathering on the Upper Stainback flow is unexpected since these particular samples were collected from beneath *Metrosideros* roots (see 'Vegetation Effects', p. 119).

TABLE XV. CHANGES IN TOTAL CALCIUM (CaO)

	Unweathered			Weathered				
Flow	No.	Mean%	S.D.	No.	Mean%	S.D.	P	% Loss
1955	10	9.29	0.21	10	9.02	0.23	< 0.05	3.0
1942	10	10.48	0.17	10	10.28	0.54	N.S.	-
1852	10	8.07	0.30	10	7.69	0.25	< 0.01	4.8
1840H	8	7.33	0.21	10	7.16	0.24	N.S.	-
1840L	10	7.36	0.28	10	7.56	0.26	N.S.	-
1750H	10	10.22	0.20	10	9.74	0.13	< 0.01	4.7
1750L	6	10.09	0.17	6	9.90	0.32	N.S.	-
Upper Stainback	9	9.77	0.27	4	8.37	0.09	< 0.01	14.3
Lower Stainback	5	9.72	0.11	5	8.79	0.07	< 0.01	9.6
Prehistoric Kapoho	5	10.00	0.23	5	9.94	0.21	N.S.	-
Honaunau	3	11.45	1.71	3	8.57	0.52	< 0.05	25.2
1855	5	10.10	0.17	5	9.85	0.22	< 0.1	2.4
Samoa 1760	3	9.58	0.09	3	9.50	0.15	N.S.	-
Upolu	5	10.45	0.21	5	10.34	0.20	N.S.	-

Accuracy = 0.35 ± 0.34% (5 determinations)

Precision = 0.12 ± 0.09% (8 determinations)

TABLE XVI. CHANGES IN TOTAL SODIUM (Na_2O)

	Unweathered			Weathered				
Flow	No.	Mean%	S.D.	No.	Mean%	S.D.	P	% Loss
1955	10	3.11	0.09	10	2.84	0.07	< 0.01	8.4
1942	10	2.34	0.06	10	2.18	0.06	< 0.01	7.2
1852	10	1.70	0.17	10	1.45	0.08	< 0.01	15.0
1840H	8	1.49	0.06	10	1.36	0.06	< 0.01	9.3
1840L	10	1.65	0.09	10	1.64	0.05	N.S.	-
1750H	10	2.52	0.14	10	2.20	0.09	< 0.01	13.0
1750L	6	2.58	0.03	6	2.49	0.05	< 0.01	3.4
Upper Stainback	9	2.53	0.06	4	1.31	0.11	< 0.01	48.3
Lower Stainback	5	2.23	0.04	5	1.71	0.09	< 0.01	23.5
Prehistoric Kapoho	5	2.41	0.07	5	2.18	0.09	< 0.01	9.6
Honaunau	3	2.69	0.62	3	1.92	0.15	N.S.	-
1855	5	2.42	0.07	5	2.44	0.08	N.S.	-
Samoa 1760	3	3.11	0.02	3	3.06	0.06	N.S.	-
Upolu	5	3.10	0.26	5	2.52	0.13	< 0.01	19.0

Accuracy = 0.07 ± 0.07% (9 determinations)

Precision = 0.07 ± 0.04% (10 determinations)

TABLE XVII. CHANGES IN TOTAL POTASSIUM (K_2O) AND MAGNESIUM (MgO)

Element as Oxide	Flow	Unweathered			Weathered			P	% Change
		No.	Mean%	S.D.	No.	Mean%	S.D.		
K_2O	1750H	10	0.51	0.02	10	0.51	0.02	N.S.	-
"	Upper Stainback	10	0.42	0.04		0.36	0.02	< 0.05	-13.6
MgO	1852	5	17.13	0.60	5	16.61	0.77	N.S.	-
"	1750H	10	3.32	0.24	10	3.28	0.27	N.S.	-
"	Upper Stainback*	5	7.90	0.47	5	8.93	0.25	< 0.01	+13.1

*Weathered samples for this analysis came from under tree roots (see p. 119).

Accuracy for K_2O = 0.07 ± 0.05% (4 determinations)

Precision " " = 0.014 ± 0.004% (4 determinations)

Accuracy for MgO = 0.19 ± 0.13% (4 determinations)

Precision " " = 0.26% (2 determinations)

Iron

Analyses for total iron (as Fe_2O_3) carried out by the Rocky Mountain Geochemical Corporation showed wide divergence from published data and the accuracy of these analyses is thus suspect. They may have some value for comparing weathered and unweathered samples. The results showed no significant gains in iron for the 1942 and 1852 flows but showed a gain of 40% of the amount of iron originally present for the Upper Stainback flow. Losses of iron, in excess of 50% of the amount originally present, were measured for the very weathered glassy crusts of the 1881 and 1855 flows.

Titanium

Analyses for this element are given in Table XVIII and in general show significant gains that increase in magnitude with time. Perhaps the most surprising result is the relatively large gain in TiO_2 measured with the 1840L samples, in contrast to the 1840H samples, where no significant gain was found. This may be related partly to the more marked dry periods of the 1840L site (p. 89).

Strontium

The measurements made on the Upper Stainback samples show that strontium is being lost with weathering (Table XIX). However, since no significant differences could be found between weathered and unweathered rocks from dated flows, no further strontium measurements were made.

Manganese and Nickel

Comparison of count rates between unweathered and weathered samples from the 1852 and Upper Stainback flows showed no significant differences for either manganese or nickel.

TABLE XVIII. CHANGES IN TOTAL TITANIUM (TiO_2)

	Unweathered			Weathered				
Flow	No.	Mean%	S.D.	No.	Mean%	S.D.	P	% Gain
1955	10	3.84	0.10	10	3.91	0.03	< 0.1	1.8
1942	10	2.09	0.02	10	2.09	0.05	N.S.	-
1852	10	1.74	0.05	10	1.77	0.04	< 0.1	2.2
1840H	8	1.73	0.05	10	1.74	0.04	N.S.	-
1840L	10	1.81	0.09	10	1.90	0.08	< 0.05	5.2
1750H	10	2.87	0.06	10	2.94	0.04	< 0.01	2.3
1750L	6	2.79	0.05	6	2.89	0.05	< 0.01	3.5
Upper Stainback	10	2.13	0.05	4	2.78	0.27	< 0.01	14.8
Lower Stainback	5	1.83	0.07	5	2.30	0.08	< 0.01	25.8
Prehistoric Kapoho	5	2.76	0.02	5	3.07	0.11	< 0.01	11.5
Honaunau	3	2.13	0.03	3	2.59	0.13	< 0.01	21.9
Upolu	5	3.75	0.03	5	4.30	0.11	< 0.01	14.7

Accuracy = 0.07 ± 0.07% (10 determinations)
Precision = 0.07 ± 0.05% (9 determinations)

TABLE XIX. CHANGES IN TOTAL STRONTIUM (Sr : p.p.m.)

	Unweathered			Weathered			
Flow	No.	Mean	S.D.	No.	Mean	S.D.	P
1942	4	520	7	4	530	9	N.S.
1852	4	470	26	4	480	19	N.S.
Upper Stainback	2	510	-	4	260	50	< 0.01

Accuracy = 30 ± 24 ppm (7 determinations)
Precision = 85 ± 47 ppm (5 determinations)

Vegetation Effects

It is important to know whether there is any significant change in the rate of rock weathering following establishment of *Metrosideros* trees. The 1750L site was chosen for a comparison between rocks from beneath a *Metrosideros* canopy and nearby surface rocks partially covered by lichens (Table XX). The *Metrosideros* sample was collected from under trees that looked to be at least 100 years old. All the differences found were small but sodium loss is definitely faster under trees. It seems probable that the calcium loss and 110 - 350°C. weight loss would have been found to be significantly greater under trees as well had it been possible to analyse a larger number of samples.

On the Upper Stainback flow recent bulldozing had overturned several *Metrosideros* trees and samples of weathered rocks were collected from beneath trunks or large roots. After analyses were completed it was realized that this had biassed the sample. The comparison between these results and those from weathered rocks collected in the usual way (Table XXI) suggests that rocks immediately underneath a large tree are protected from leaching and are markedly different from surrounding surface rocks.

Weathering and Vegetation Development on Pahoehoe and Aa Flows

Surface Glassy Crusts of Pahoehoe

Table XXII compares the measurements made of surface glassy crusts (VW = very weathered samples) from the 1855 and 1881 pahoehoe flows with those of weathered (W) rock samples from the 1852 aa flow. The sampling sites were between 3660 and 3800 feet in altitude. From these figures it appears that pahoehoe surfaces weather much more rapidly than small rocks on aa surfaces.

TABLE XX. COMPARISON OF ROCKS WEATHERED UNDER A METROSIDEROS CANOPY WITH THOSE FROM ADJACENT BARE LAVA (1750L SITE)

Variable Measured	Under Trees (6 samples)		Bare Lava (6 samples)		p
	Mean	S.D.	Mean	S.D.	
pH_{H_2O}	7.40	0.18	7.37	0.16	N.S.
pHc	2.62	0.25	2.69	0.17	"
Na_2O %	2.49	0.05	2.59	0.06	< 0.05
CaO %	9.90	0.32	9.97	0.29	N.S.
Weight loss %	2.15	0.45	2.02	0.22	"

TABLE XXI. COMPARISON OF ROCKS WEATHERED BENEATH METROSIDEROS ROOTS WITH THOSE WEATHERED AMONG ROOTS: UPPER STAINBACK FLOW

Variable Measured	Beneath Roots (6 samples)		Among Roots (4 samples)		p
	Mean	S.D.	Mean	S.D.	
pH_{H_2O}	7.26	0.23	6.79	0.23	< 0.05
pHc	3.12	0.29	3.41	0.25	< 0.01
Na_2O %	2.21	0.10	1.31	0.11	< 0.01
CaO %	9.75	0.12	8.37	0.09	< 0.01
K_2O %	0.44	0.02	0.36	0.02	< 0.01
TiO_2 %	2.23	0.06	2.78	0.27	< 0.01
Weight loss %	1.17	0.56	3.28	0.44	< 0.01

TABLE XXII. COMPARISON OF GLASSY CRUSTS OF PAHOEHOE WITH WEATHERED AA ROCKS

Flow	Mean Ann. Rainfall (in.)	No. of Samples	pHc	ΔpH	110-350° Weight Loss %	Pigeonite/ Hypersthene Ratio	Iron Loss %
1852	210	10	2.07	0.37	0.94	0.98	N.S.
1855	250	4	3.07	0.77	1.32	1.90	58
1881	220	4		0.31	1.06	0.88	53

Weathering on Pahoehoe and Aa Flows

Previously tabulated data for two pahoehoe and three aa flows is combined in Table XXIII, together with some information on the 1793 pahoehoe flow of Kilauea. Any surface glassy crusts present on the pahoehoe flows had been removed before analysis of the weathered rocks. The 1855 pahoehoe and 1852 aa sites are at the same altitude and less than 3 miles apart but the pahoehoe flow receives 40 inches more rainfall. The Samoan 1760 pahoehoe site has more rain and higher temperatures than the 1750L Hawaiian aa site. However, the 1793 and 1840H sites on Kilauea are within a mile of each other and have similar rainfall and temperatures.

It appears that sodium is being lost more rapidly from the aa flows but the weight loss and pHc measurements show that other weathering changes are not always correlated with loss of bases. The higher pHc value for the 1855 pahoehoe flow could be related to the high rainfall of this site.

The low altitude comparison on the Kilauea flows shows that vegetation development is occurring much more rapidly on aa flows. The high altitude comparison on Mauna Loa does not show a large disparity between pahoehoe and aa sites where the differences measured could be a result of sampling error.

TABLE XXIII. WEATHERING AND VEGETATION DEVELOPMENT ON THREE PAIRS OF PAHOEHOE AND AA FLOWS

	Mauna Loa		Savaii	Kilauea	Kilauea	Kilauea
	1855	1852	1760	1750L	1793	1840H
Type of lava	pahoehoe	aa	pahoehoe	aa	pahoehoe	aa
Altitude	3660	3660	550	300	650	650
Mean annual rainfall	250	210	125-150	90	130	130
Mean annual temperature	60.4	60.4	77.0	72.1	70.9	70.9
pHc	2.89	2.07	1.09	2.62	-	-
Calcium loss %	2.4	4.8	N.S.	N.S.	-	-
Sodium loss %	N.S.	15.0	N.S.	3.4	-	-
Weight loss %	0.93	0.94	0.44	2.15	-	-
Metrosideros ht. (m)	2.1	2.2	-	-	4.6	7.5
" d.b.h.(cm)	2.5	3.9	-	-	9.6	21.5
" cover %	28	12	-	-	36	52
Fern cover %	26	48	-	-	60	48
Organic horizon depth (cm)	5.0	11.9	-	-	2.6	0.8

AGE DETERMINATIONS

Multiple linear regression methods were considered to have the greatest potential for estimating the ages of the undated prehistoric flows. Using the data from the dated flows, regression equations were computed with time as one of the variables. Such equations could then be solved for time using measurements from the undated flows. Two questions to be answered were:

(i) What variables should be used in the regression equations and how should they be expressed?

(ii) How could the "best" regression equation be selected?

Variables for Regression

Weathered Rock Parameters

Six parameters of the weathered rock were selected from those measured as having greatest potential for age indices. These were ΔpH, pH change, 110-350°C. weight loss, calcium loss, sodium loss, and titanium gain. Three additional variables, derived from the above, were also used in the regression equations: sodium loss relative to titanium gain, calcium loss relative to titanium gain, and the combined loss of calcium + sodium.

The regression analysis was made using the data for these variables from the 5 historic aa flows (7 sites in all). Measurements had been made on 10 samples from each of 6 sites while the seventh site (1750L) had 6 samples. Thus there was a total of 66 groups of measurements from flows ranging in age from 13 to 218 years.

The mean of the 10 unweathered samples was taken as the best estimate of the original value of the variable in the unweathered lava. Changes in pH, and elemental losses and gains were then calculated for each of the 10 weathered samples using this mean as a baseline. On aa flows there is no logical basis for pairing weathered and unweathered samples. With the ΔpH and weight-loss measurements, only those from the weathered rocks were used in the regression analysis.

The sodium and calcium losses relative to titanium were calculated using a method based on that of Reiche (1943):

$$\% \text{ loss} = 100 - \left(\frac{V_w \times Ti_u}{V_u \times Ti_w} \times 100 \right)$$ where V_w is the measurement of sodium or calcium in the weathered rock, V_u is the mean of the sodium or calcium measurements for the unweathered samples, and Ti_w and Ti_u are the means of the titanium measurements for weathered and unweathered rocks. This calculation makes no assumptions about the 'constancy' of titanium but stretches the scale of differences.

All the above variables were used both as dependent and independent variables in the regression equations.

Soil and Vegetation Parameters

Two parameters were used in the regression analysis: depth of the soil organic horizon and log. of tree volume.

Climatic Factors

Each site was given a single value for temperature and for rainfall. A temperature x rainfall interaction was also used as an independent factor in the regression analyses. Mean annual temperatures were calculated from the data of Blumenstock and Price (1967) using a lapse-rate of 3.5°F./1000 feet. Mean annual rainfalls were taken from the map by the same authors (see Table II).

Parent Material Factors

Four properties of the parent material were used: porosity, texture, titanium content, and the combined calcium + sodium content. Porosity and texture were assessed for individual samples as described under "Analytical Methods". The single values for each site used in the regression analysis were means of the individual ratings given to the unweathered rocks. Titanium and the combined calcium + sodium contents of the parent material were obtained from the mean values of the unweathered samples.

Age

The age in years of each historic flow was calculated using 1968 as a baseline.

Topography

Since sampling was restricted to sites of less than 10° slope, the effects of topography were assumed to be the same for all sites.

Effective Plant Factor

Jenny (1941, 1958, 1961) in developing his factorial approach to soil genesis and ecosystem development, treated the biotic factor as comprising all those species, or their propagules, which may migrate or be carried into the ecosystem. With this approach, vegetation within the ecosystem is a dependent variable or resultant, whereas the biotic factor is relatively independent of the ecosystem studied and determines the potential vegetation of the system. Jenny (1958) suggested that a list of the species in the ecosystem and those living in the surrounding area could be used to characterize the total biotic factor.

Crocker (1952) pointed out that in any particular case only some of these species are effective pedogenetically, namely, the species present in the system and those formerly present but lost during its development. He suggested that an effective plant factor could be measured by listing these species, using successional studies to indicate which had been lost during development.

Species lists are difficult to quantify for analyses such as correlation and regression. Furthermore, different species from different floral regions may have similar pedogenetic effects. Without knowing what these effects are it is not possible to compare the biotic factor of different ecosystems as we can compare temperature, rainfall or parent material factors. As appreciated by Crocker (loc. cit.) the pedogenetic effects of different plants are not simply associated with numbers. Nevertheless, only those plants that have contributed a major portion of the cover at any time during the succession need be considered. The effects of many other plants are probably minor because of their small size or number. The most needed information is how the major species differ in their physical, chemical and biological effects on ecosystem changes.

Because of the lack of information on the specific effects of plants on pedogenesis, it was decided to use the litter pH of major species as a measure of the chemical effect each might have. A major species was defined as any species that had formed 20% or more of the canopy at any stage during the succession. For each major species the value 14 - litter pH (=pOH) was calculated, which gives a scale from zero to 14 reflecting the varying effects on weathering of litters of different pH. The effective plant factor for each site was calculated by averaging the litter pOH of all major species. For example, on a 200 year old flow where a major species A had been replaced by a major species B after 100 years, the effective plant factor would be:

$$\frac{(100 \times \text{litter pOH of species A}) + (100 \times \text{litter pOH of species B})}{200}$$

Effective plant factors for each site sampled on Hawaii are given in Table XXIV together with the assumptions made in calculating these factors.

An effective plant factor measured in this way is not wholly independent of the ecosystem studied. The degree of cover reached by a particular species is partly related to local climate, parent material and to time. Litter pH may be partly affected by site conditions. However, the capacity of a species to affect soil and vegetation is determined by its inherent physiological properties even though the expression of these properties is conditioned by the particular ecosystem. The use of litter pH values is a first approximation towards measuring differences between species in their pedogenetic effects and thus quantify an effective plant factor to which differences in dependent variables of the ecosystem (soil and vegetation properties) can be related.

Climatic, parent material and effective plant factors are referred to as site factors for the regression analyses and the values used are given in Appendix II. Dependent variables are classified as either weathered rock, soil or vegetation parameters.

Selection of Regression Equations

Two types of regression equation can be formed with the variables discussed above. In the first, time can be treated as a dependent variable and regressed against various combinations of the measured rock parameters and site factors. In the second, a suitable parameter of the weathered rock is chosen as the dependent variable and regressed against various

TABLE XXIV. EFFECTIVE PLANT FACTORS FOR SITES SAMPLED

Flow	Effective Plant Factor	Assumptions
1955	0.0	
1942	0.0	
1852	5.7	50 yrs for *Dicranopteris* to reach 20% cover *
1840H	7.7	30 years for *Dicranopteris* to reach 20% cover
1840L	4.5	60 years for *Metrosideros* to reach 20% cover
1750H	8.8	20 years for *Metrosideros* to reach 20% cover
1750L	7.5	50 years for *Metrosideros* to reach 20% cover
Upper Stainback	9.9	Mean value of *Metrosideros* and *Cibotium* litter pOH measurements
Lower Stainback	9.7	*Metrosideros* as major species for an unknown period of time
Honaunau	9.7	*Metrosideros* as major species for an unknown period of time
Prehistoric Kapoho	8.3	Mean value of *Pandanus* and *Metrosideros* litter pOH measurements

*An approximate time for a species to reach 20% cover was calculated from the current percentage cover for that species and the age of the site.

combinations of site factors, other rock parameters and time.

Krutchkoff (1967) using simulations, studied the first approach when applied to the problem of calibrating a pressure gauge. He claimed a uniformly smaller mean square error than that associated with the second or classical procedure. However Williams (1969) pointed out that the first approach gives estimates based on the false assumption that the errors are independent of the values of the dependent variable, thus violating the assumptions of a regression model. In an earlier publication, Williams (1959) recommends using a classical type regression equation in which the variable of interest (in this case time) is solved for inversely to give estimates together with confidence limits.

i.e. if $Y = \beta_0 + \beta_T T + \beta_2 X_2 + \beta_3 X_3 + \ldots\ldots\ldots\ldots \beta_j X_j$

then $T = \dfrac{Y - \beta_0 - \beta_2 X_2 - \beta_3 X_3 - \ldots\ldots\ldots\ldots \beta_j X_j}{\beta_T}$

where Y = dependent variables, T = time, X_2, X_3 = other independent variables and $\beta_0 \ldots\ldots\ldots \beta_j$ = regression coefficients.

Although both procedures were tried in the present study, the inverse estimation method was used for the age determinations since it allows statistically valid confidence limits to be calculated for time:

$$T = \frac{Y - \beta_0 - ..\beta_j X_j}{\beta_T} \pm \frac{t.\sqrt{\text{residual mean square}}}{\beta_T}$$

where t = the t statistic for n degrees of freedom with 95 or 99% confidence levels. These are the large sample confidence limits which assume that the errors in estimating the regression coefficients are small relative to the error in the regression equation. The sample sizes used justify this assumption if inverse estimates are not attempted for times too far beyond the data (Dr. R. Jones, Information Science Dept., University of Hawaii, pers. comm.).

A recent example of the use of an inverse procedure is that of Julian and Fritts (1968). They first established a linear regression relationship between tree-ring chronology and historic climatic data, and then inverted this to derive climatic records from prehistoric growth-ring sequences.

Initially, all the data from the dated flows was used in the regressions but a number of these equations gave ages for prehistoric flows that were clearly erroneous. Study of the residuals showed them to be somewhat asymmetrically distributed. The correlation matrix (Appendix IV) indicated that spurious correlations were arising because the oldest flows (1840 and 1750) were at the lowest altitudes. Furthermore, there were larger numbers of measurements for these two flows both having two sampling sites. For these reasons the data from the lower site of each (1840L and 1750L) were excluded, leaving 5 flows with one site per flow (50 sets of measurements = 49 degrees of freedom).

Separation of these lower sites from the remainder is probably justified also on climatic grounds. Both sites are only partially covered by vegetation whereas the 1840H and 1750H sites are completely covered. The lower sites are fairly close to the coast where there is apparently a greater tendency for summer-dry periods to occur. These are accentuated by the excessively drained aa lava. The climate of the remaining sites is both cooler and more humid.

Selection of the regression equation used for aging the Stainback prehistoric flows was made by making several series of regressions and then choosing the equation that met the following requirements most completely:

1. Narrow confidence limits for time.
2. A high multiple R^2 value (R = multiple correlation coefficient) so that a large proportion of the total variability is accounted for by the regression.
3. Statistically significant regression coefficients for the variables used in the equation, particularly the regression coefficient for time.
4. Residuals which when plotted against time do not show a trend.

Some equations with high R^2 values gave ages that were very obviously incorrect. Presumably these equations did not describe any general model of processes operating between the variables used.

Each of the weathered rock parameters together with their derived variables (e.g. sodium loss relative to titanium, see preceding section) were regressed on the variables of time, climate, parent material and effective plants. Significant regression coefficients for time appeared in only three cases: pHc, weight loss, and calcium loss relative to titanium (Table XXV). The respective R^2 values for each of these regressions were 65%, 55%, and 26%. From this it appeared that only pHc and weight loss were likely to be useful age indices. A series of computer runs was made in which pHc and weight loss, or their transgenerated derivatives, were regressed on various combinations of variables. The resulting equations were then tested for the requirements listed above.

The regression program (BMDO2R) used in this work is a stepwise procedure in which one variable is added at a time depending on which makes the largest improvement in "goodness of fit". At later stages in the regression a variable may be dropped, this being dependent on the F level set for deletion of variables.

TABLE XXV. SUMMARY OF REGRESSIONS OF WEATHERED ROCK PARAMETERS ON INDEPENDENT VARIABLES: DATED FLOWS, FIVE SITES

Rock Parameter	Independent Variables with Significant Regression Coefficients	F Ratio	R^2
ΔpH	Rainfall, effective plant factor	36.6	61%
pHc	Time, titanium content, rainfall	29.0	65%
Sodium loss	Temperature x rainfall, calcium + sodium content	14.6	38%
Calcium loss	No significant regression	1.5	12%
Titanium loss	No significant regression	2.5	18%
Weight loss	Time, temperature x rainfall	29.2	55%
Sodium loss rel. to titanium	Temperature x rainfall, calcium + sodium content	20.1	46%
Calcium loss rel. to titanium	Time, titanium content, rainfall	5.4	26%
Total calcium + sodium loss	Temperature x rainfall, calcium + sodium content	4.8	19%

Results of Age Determinations

Regression Equations used for Aging

A few equations met the requirements listed (p. 131). Of these, the highest R^2 (80%) and narrowest confidence interval ($\pm$ 87 years) were associated with an equation which used $(pHc)^2$ as a dependent variable (Equation 1):

$$(pHc)^2 = -0.54 - 0.08\,(\text{Na loss}) + 0.27\,(\text{Ca loss}) + 0.02995\,(\text{Time}) - 0.29\,(\text{Rock porosity}) + 1.21\,(\text{Ti content}).$$

Regression coefficients and the analysis of variance for this equation are given in Table XXVI together with age determinations for the Upper and Lower Stainback flows.

The most satisfactory equation for weight-loss had an R^2 value of only 55% and a confidence interval of $\pm$ 108 years (Equation 2):

$$\text{Weight loss} = 0.66 + 0.00795\,(\text{Time}) + 0.00005\,(\text{Temp.} \times \text{rainfall})$$

Details of this equation and the associated age determinations are given in Table XXVII.

There is reasonable agreement between the two equations for the ages of the Upper and Lower Stainback flows. It may be noted that these two equations use different sets of dependent and independent variables, apart from time. The pHc ages of c. 360 years are probably more reliable than those derived from the weight-loss regression because of the higher R^2 and narrower confidence interval of the pHc regression equation.

A calculation of the age of the Honaunau flow using equation 1 gave an age within the historic period. It is more likely that the calcium loss measurement for this site is too large (see p. 113) and therefore the age determination based on the weight-loss regression (Table XXVII)

TABLE XXVI. AGE DETERMINATIONS FROM EQUATION 1: pHc REGRESSION

Multiple R^2 = 80%. Confidence limits for time: ± 87 years.

Standard error of estimate : 1.294

Dependent variable: $(\mathrm{pHc})^2$ Constant of equation: -0.538

Variables in Equation	Regression Coefficients	Standard Error	F Value
Sodium loss	-0.082	0.052	2.48
Calcium loss	0.272	0.061	19.76
Time	0.02995	0.003	108.36
Porosity	-0.286	0.126	5.14
Titanium content	1.211	0.240	25.51

Analysis of Variance

	df	mean square	F ratio
Regression	5	58.764	35.11
Residual	44	1.674	

Age Determinations

Upper Stainback flow: 359 ± 87 years

Lower Stainback flow: 362 ± 87 years

TABLE XXVII. AGE DETERMINATIONS FROM EQUATION 2: WEIGHT-LOSS REGRESSION

Multiple R^2 = 55% Confidence limits for time: ± 108 years.

Standard error of estimate: 0.425

Dependent variable: 110 - 350°C. weight loss.

Constant of equation: 0.661

Variables in Equation	Regression Coefficients	Standard Error	F Value
Time	0.00795	0.00112	50.14
Temperature x rainfall	0.00005	0.00002	8.34

Analysis of Variance

	df	mean square	F ratio
Regression	2	5.279	29.18
Residual	47	0.181	

Age Determinations

Upper Stainback Flow :	383 ± 108 years.
Lower Stainback Flow :	341 ± 108 years.
Honaunau Flow :	254 ± 108 years.

is probably nearer the real age of this flow. The number of samples from the site (3) needs to be increased before further age calculations are attempted.

Age Extrapolations

Eliminating the data of the 1840L and 1750L sites from the regression analyses prevents use of the equations to age the prehistoric Kapoho flow. On these two sites, time was again most strongly correlated with pHc and weight-loss. Straight-line extrapolations of the measurements from these sites, allowing for differences in altitude, gave a "pHc age" for the Kapoho site of 320 years and a "weight-loss age" of 305 years.

Similarly, any idea of the age of the prehistoric pahoehoe flow of Upolu, Samoa, can only be approximated by extrapolation from the Savaii 1760 site. Both pHc and weight-loss extrapolations suggest the Upolu flow is at least 600 to 900 years old.

Sources of Error in Applying the Regression Equations

As discussed by Esekiel and Fox (1959), applying a regression equation to estimate values that are beyond the range of the observed data on which the equation is based is hazardous, since the error estimates may no longer be accurate. In the present case, there are no dated flows spanning the prehistoric period studied. Thus if a first approximation of the ages of the prehistoric flows is to be made, there is no alternative but to exceed the measured range of dependent variables such as pHc and weight loss. Considering the independent variables apart from time, the range of each of these variables used in computing the equations is given in Table XXVIII. The mean annual temperature of the Lower Stainback site (72.1°F.) slightly exceeds the original range. With the Honaunau flow, both mean annual rainfall and the combined calcium +

TABLE XXVIII. RANGE OF VALUES FOR INDEPENDENT VARIABLES USED IN REGRESSION EQUATIONS

Variable	Range
Time	13 - 218 years
Rainfall	100- 210 inches
Temperature x rainfall	7600 - 12,600 units
Temperature	60.2 - 70.9° F.
Effective plant factor	0 - 8.8 units
Rock texture	4.0 - 9.6 units
Rock porosity	2.5 - 6.6 units
Calcium + sodium content	8.83 - 12.82%
Titanium content	1.73 - 3.84%

sodium content of the rock, are beyond the range used for the regression equation.

All these age calculations assume that the relationship between the variables studied is linear. A curvilinear estimation from measurements of only five dated flows, that are rather unevenly distributed with respect to time, might be misleading. If, as seems probable, some weathering changes are curvilinear in the time span covered, then the real ages of these flows will tend to be older than those given.

DISCUSSION AND CONCLUSIONS

In this discussion the results for vegetation and rock measurements will be related to the question of trends and rates of change in the lava-flow ecosystems studied. It must be borne in mind that the conclusions reached are derived from studying the early stages (< 400 years) of development and that these flows are situated in a comparatively wet part of Hawaii (90 - 250 inches rainfall). In the final parts of the discussion some suggestions are made for further studies.

Trends Within the Ecosystem

Successional Trends on Aa Flows

The most obvious feature of these early stages of lava-flow succession, is the dominance of *Metrosideros polymorpha*, a fact commented on by many observers. The only exception to this is on young flows in the zone immediately behind the shoreline, where for 100 meters or more the species is largely absent. Further back from the shoreline for a distance of 200 - 300 meters, *Metrosideros* increases rapidly in numbers and size as for example on the coastal portions of the Kilauea 1840 and 1750 flows. Further inland again the number and size of *Metrosideros* plants become typical for the lower part of the flow as a whole.

In spite of the widespread dominance of *Metrosideros*, in no part of the area studied does it appear that the species is stable. The figures for height-class distribution (Table VI) indicate a steadily decreasing rate of seedling establishment with increasing time.

Although Metrosideros density was found to be extremely variable, it is clear that seedlings may continue to establish for at least 100 years if suitable rock crevices are available (Table V). Thus on any one site, Metrosideros tends to increase in numbers and cover during the first 100 years of succession.

Sometime during the second hundred years of succession, regeneration of Metrosideros ceases, and trends of partial replacement by other species are initiated. Near the coast there is evidence of replacement by Pandanus tectorius; while inland below 1000 feet, there are indications of partial replacement by Diospyros ferrea and Psychotria hawaiiensis. At higher altitudes Cibotium tree-ferns form more of the canopy with increasing time. In the rainfall zone of 180 inches or more, many other species appear in the canopy, as for example along the Stainback Highway. However the trends here have not been studied. The evidence for decreasing Metrosideros cover and numbers lies in the absence of seedlings and saplings from shaded ground. It is not unlikely, however, that at a future stage beyond the 400 year time-span studied, the Metrosideros could reach an equilibrium when replacement balances mortality. Such replacement could occur by resprouting from old trees and occasional establishment of seedlings on tree-fern trunks.

Successional Trends on Pahoehoe Flows

From the point of view of floristic composition there appears to be little difference between the successions on aa and pahoehoe flows in this wet region. In comparing plant establishment on the drier aa and pahoehoe flows of Hawaii, Forbes (1912), Robyns and Lamb (1939) and Skottsberg (1941) found that lichens established more rapidly on aa surfaces, while on pahoehoe higher plants established first, particularly in crevices. This may also be true for flows in wet regions but recent pahoehoe flows were absent from the study area. As remarked earlier, on older pahoehoe flows in the Stainback-Saddle road segment of Mauna Loa, juvenile _Cheirodendron trigynum_ appears to be more frequent than on aa flows of comparable age.

Considering vegetation structure, the density of _Metrosideros_ trees is often lower on pahoehoe than aa although this is by no means invariably the case. The reasons for this are discussed on p. 143.

Weathering Trends on Aa Flows

The main trends among the weathered rock parameters measured are clear. With increase in weathering there is a decrease in rock pH, an increase in ΔpH, a loss of sodium and calcium, and a relative gain in titanium. Water and hydroxyl ions are added to the system. Sodium and calcium losses can be related to weathering of the plagioclase felspars, and would be an important factor influencing decrease in pH. These ions, though lost from the weathering rock, are not necessarily lost from the ecosystem: wherever accumulation of organic matter has occurred there is the possibility of cation adsorption on the organic exchange complex.

These trends in elemental percentages are similar to those already known for more weathered lavas (McGeorge 1917, Harrison 1934, Goldich 1938). This study shows that some of these changes are considerable even on flows less than 50 years old.

Similar trends to those for rock pH have been found for the abrasion pH of weathered andesites (Hendricks and Whittig 1968) and granite

(Grant 1963). Again, the magnitude of the change within the historic period is noteworthy.

The elemental, pH and weight-loss parameters could all be used as weathering indices, separately from any value they may have as age indices.

Losses of silicon, potassium and strontium, and gains of aluminum and iron are apparently not significant during the first 200 years of weathering but become so during the following 200 years (Tables XIV, XVII, XIX). The magnesium gains measured on the Upper Stainback flow (Table XVII) may possibly be related to the comparatively large size of the olivine phenocrysts which would retard their rate of weathering.

No measurements were made of the amounts of clay formed but it was apparent that some clay formation had occurred at the two Stainback sites.

The local effects of tree growth on the rate of rock weathering must not be ignored when sampling an historic or late prehistoric flow (p. 119). These effects could result in a marked pattern of heterogeneity on a flow during the early stages of succession. With increasing time and after several generations of trees, it seems likely that these local differences will disappear.

Weathering Trends on Pahoehoe flows

The main trends described for aa flows are occurring also on pahoehoe flows, although usually more slowly. However, in the surficial glassy crusts discussed earlier (p. 119) rapid weathering occurs with consequent release of mineral nutrients. This will be of most significance to plant growth where moisture is not limiting, as for example on the pahoehoe flows of the study area. Since the vesicles are rather unconnected in pahoehoe, it is relatively impervious to water. Thus heavy rain would tend to wash the nutrients released from the weathering crusts into crevices and fissures.

It can be expected that both weathering and succession on pahoehoe flows will be increased where aolian or colluvial material has collected in depressions on the lava surface.

Rates of Change in Lava-Flow Ecosystems

Factors Affecting Trends and Rates of Succession

Only tree-volume estimates were used in the regression analyses because of the limited number of vegetation samples. However, some generalizations are possible based on the sampling and other observations made over a wider area.

General observation shows that the most important factor affecting the rate of succession is available moisture as determined by total rainfall, rainfall distribution and edaphic factors. Even in the high rainfall of the area studied, it appears that available moisture can still restrict plant growth on a lava flow. The two most important edaphic factors influencing available moisture on an aa flow are the size distribution of boulders and stones and the porosity of individual rocks. A flow composed mainly of large boulders has less cover of *Metrosideros* trees than one consisting of smaller stones and gravels. For example, the *Metrosideros* cover of the 1852 site (Table VIII) is less than half that of the 1855 pahoehoe site.

Rock porosity appears to influence especially the establishment of the lichen *Stereocaulon vulcani*. The 1955 site is particularly scoriaceous and porous and here *Stereocaulon* is extremely abundant.

The rock porosity rating was 4.88 (Appendix II), second only to the 1840H site, but this rating does not appear to reflect fully the very porous and crumbly condition of this flow. It seems that a measure of the particle coherence of rock samples is also needed.

On pahoehoe flows, the establishment of Metrosideros appears to be at least partly controlled by the presence of fissures and cracks, a point appreciated particularly by Skottsberg (1941). A flow with few fissures tends to have a lower density of Metrosideros than a strongly fissured flow. The fissures act as traps for wind-blown dust and possibly also for mineral nutrients released during weathering of the pahoehoe crust (see "Weathering Trends on Pahoehoe Flows"). Accumulation of this fine material would increase moisture storage. Forbes (1912) remarked on the fertile soil that develops in pahoehoe cracks. In addition to these factors of nutrient and moisture supply, a fissure provides space for the development of roots. Thus a strongly fissured pahoehoe flow can support a Metrosideros stand of similar density to an adjacent aa flow of the same age.

A feature particularly characteristic of pahoehoe flows is the common occurrence of "air-gaps" or small tunnels several feet below the surface. These are formed during emission of the flow after the upper surface has solidified but while molten lava is still moving deeper down. These tunnels, in removing water rapidly, may also contribute to moisture shortage on pahoehoe flows.

An indirect effect of moisture on the trend of succession occurs with the fern Dicranopteris linearis. On both aa and pahoehoe flows, Metrosideros regeneration largely ceases as this fern spreads. Where Dicranopteris forms dense tangled thickets, particularly at lower altitudes, *Metrosideros* seedlings are not found. Establishment and growth of Dicranopteris appears to be intimately related to available moisture: on drier sites such as the lower part of the 1750 flow, this fern is infrequent.

An interesting question concerns the reason why succession, in terms of the development of a tree understorey and the partial replacement of the canopy, has progressed further on the upper 1750 site (990 feet) than on the much older (c. 1600 A.D.) Lower Stainback site (300 feet). The 1750 site has a well developed understorey of *Diospyros ferrea* and in some places this species is replacing *Metrosideros*. A *Cibotium* tree-fern understorey has developed on the Stainback site although there is little mortality of *Metrosideros*. Because of its probable secondary status, the Lower Stainback forest may not be greatly different in age from that of the 1750 site. However there is no evidence that *Diospyros* will ever be an important species there.

It seems possible that rainfall differences may explain these contrasting successional trends since Mueller-Dombois (1966) describes open *Metrosideros-Diospyros* forest on steep slopes within Hawaii Volcanoes National Park. In the Park this community is associated with a summer-dry climate. Such conditions may occur to a limited extent in the 110 inch rainfall of the Kilauea 1750 site, but are unlikely in the Stainback area of Mauna Loa, where the rainfall is 140 inches and cloud cover is frequent. From this it can be inferred that increasing rainfall in the range 110 to 140 inches, or possibly increasing cloud cover associated with this rainfall difference, has altered the trend of succession. Whether the rate of succession has also been altered is not clear in this case.

Comparison of the 1750 H site with the 1750L site (90 inch rainfall) shows a reduced growth rate on the latter site (Table VIII), indicating that here the rate of succession has been reduced. Although Diospyros was not present on the 1750L site, Metrosideros-Diospyros forest occurs in still lower rainfall within the National Park and thus there is no reason to suppose that the trend of succession has been altered.

The regression analysis of tree-volume estimates on the historic flows (Table XXIX), showed that time, rock porosity and rainfall (with a negative regression coefficient) were the most important factors "accounting" for differences in mean tree volume. The negative coefficient for rainfall is a result of the fact that the highest growth rates are associated with the driest (and warmest) sites.

From the foregoing discussion it can be seen that rainfall, or factors associated with it, is affecting trends and rates of succession in this high-rainfall region. With aa flows having similar rainfall, differences in the rate of succession may still develop because of differences in rock porosity and rock size that affect available moisture.

Factors Affecting Trends and Rates of Weathering

The regression analyses allow the effects of time and the various site variables to be separated. Table XXIX summarizes the results from regressing weathered rock and tree volume parameters on site factors and time. The first group of regressions is that based on the 66 samples from the historic flows. The second group based on 75 samples, includes data from the two most reliably dated prehistoric flows: the Upper and Lower Stainback. The independent variables of the equations (site factors and time) having significant regression coefficients are numbered in order of their F values. Negative regression coefficients are indicated after the number. The variables in regression equations

TABLE XXIX. SUMMARY OF FACTORS HAVING SIGNIFICANT REGRESSION COEFFICIENTS IN REGRESSIONS OF WEATHERED ROCK PARAMETERS ON SITE FACTORS AND TIME

HISTORIC FLOWS

	Weathered Rock and Vegetation Parameters						
Site Factors	ΔpH	pHc	Sodium Loss	Calcium Loss	Titanium Gain	110-350°C. Weight Loss	Tree Volume Estimate
Time		1				1	1
Rainfall		3	1				2 -
Temperature	2 -		4 -				
Plant factor	1		2				
Porosity	4			3		3	3
Texture		4		1 -			
Ca + Na content				2		2	
Titanium content	3	2	3	4 -			
R^2 (%) for each regression	72	67	61	34	28	62	93

Note: Regression coefficients in this table are numbered in order of the size of their F values.

TABLEX XXIX (Continued) SUMMARY OF FACTORS HAVING SIGNIFICANT REGRESSION COEFFICIENTS IN REGRESSIONS OF WEATHERED ROCK PARAMETERS ON SITE FACTORS AND TIME

HISTORIC AND PREHISTORIC FLOWS

	Weathered Rock and Vegetation Parameters					
Site Factors	ΔpH	pHc	Sodium Loss	Calcium Loss	Titanium Gain	110-350°C. Weight Loss
Time	4	1	3		1	1
Rainfall	3					4
Temperature	5		1 -		3 -	
Plant factor	6 -		5		4 -	
Porosity	1		4			3
Texture			2 -			
Ca + Na content	2	2			2 -	2
Titanium content					5	
R^2 (%) for each regression	79	68	83	30	82	76

having R^2 values of 30% or less, have not been listed. The frequency of each of the independent variables in the equations for the weathered rock parameters (only) is listed below.

Independent Variable		Historic Flows		Historic and Prehistoric Flows	
Climate:	rainfall	2	4	2	5
	temperature	2		3	
Time		2		5	
Effective plant factor		2		3	
Rock composition:	Ca + Na content	2	6	4	5
	Ti content	4		1	
Rock structure:	texture	2	5	1	4
	porosity	3		3	

From this analysis it is apparent that no one factor or group of factors stand out as being of paramount importance in weathering. Differences in climate, time, effective plants, rock composition, porosity and texture are all influencing variation in the parameters measured. Slope and other topographic variables could not be included since these factors had been kept constant during sampling. A different regression program (e.g. a step-down fitting procedure in which variables are progressively deleted) might have picked different combinations of variables. However it seems unlikely that their overall distribution would be greatly altered.

Temperature may be related to weathering positively by increasing the rate of chemical reactions, or negatively by increasing evaporation and thus decreasing the amount of water that passes through the surface rocks. In 4 out of 5 cases, temperature appears in the equations with a negative coefficient. This suggests that, in the climatic range studied, it is the evaporation effect which is more important. It may explain why the Savaii 1760 pahoehoe flow in Samoa, at a mean annual temperature of 77°F., is weathering more slowly than the 1855 pahoehoe flow in Hawaii at a mean annual temperature of 60°F. (Table XXIII).

Some of the site variables are significantly correlated with each other (Appendix IV). This can sometimes result in the replacement of one variable by another that has no functional relationship with the dependent variables regressed. Highly correlated site variables can also result in changes of sign in the regression coefficients that are difficult to interpret. For example, the titanium content invariably appears in the equations with a positive coefficient. At first sight this would imply that the rate of weathering increases with increase in titanium content of the parent rock: a surprising conclusion in view of the known stabilizing effect of titanium on mineral structure. However, a plotting of titanium content of the parent rock against sodium content, showed that with the historic flows sampled, the two variables are highly correlated. The rate of weathering may well be associated with sodium content since this would reflect the content of easily weatherable minerals. Study of Macdonald and Katsura's (1964) data shows that there is no general relationship between titanium and sodium content in tholeiitic lavas.

An estimate of the quantitative effects on weathering of site factors and time, (the state factors of Jenny, 1961), is possible by considering the magnitude of the regression coefficients associated with those regression equations having high R^2 values. These coefficients correspond to the partial differentials of a Jenny-type equation. This has been done for the factors time, rainfall, temperature, effective plants, porosity and calcium + sodium content of the unweathered rock (Table XXX). The figures of this table are taken directly from the regression coefficients. They show the amount of change in a dependent variable that can be associated with a fixed amount of change in a particular independent variable. In each case the effects of other independent variables are nullified.

Porosity and Ca + Na content of the rock, appear to be the most important factors affecting change in ΔpH values. As shown earlier (p. 93), ΔpH measurements probably indicate change in solubility of the rock constituents rather than development of cation exchange capacity.

Combined Ca + Na content is also of importance in affecting pHc values. This factor appears with porosity in the regression equations for weight loss. While an effect of porosity on weathering is not surprising, an effect of chemical composition was not expected since all the flows sampled are essentially either basalts or olivine basalts.

With the regressions for calcium loss and titanium gain on the historic flows, and calcium on the combined historic and prehistoric flows, the percentage of variability explained by the regressions is very low (Table XXIX). This implies either that there are unknown variables causing variation in these parameters or that the relationship is curvilinear rather than linear.

The equations for sodium loss indicate a considerable effect of the effective plant factor ($>$ 2% loss of sodium per pOH unit of effective plants). This is in agreement with the results obtained for sodium

TABLE XXX. QUANTITATIVE EFFECTS OF INDEPENDENT VARIABLES ON WEATHERING

	Δ pH*	pHc*	Na Loss**	Ti Gain**	Weight Loss %	Tree Volume Estimate***
Change/100 years						
Historic flows	-	0.84	-	-	0.63	175
Historic + prehistoric	0.17	0.59	9.8	19.0	0.68	-
Change/10 inch rainfall						
Historic flows	-	0.14	1.23	-	-	-1.1
Historic + prehistoric	0.05	-	-	-	0.04	-
Change/°F. temperature						
Historic flows	-	-	-0.16	-	-	-
Historic + prehistoric	-	-	-0.56	-0.29	-	-
Change/Unit plant factor						
Historic flows	-	-	2.02	-	-	-
Historic + prehistoric	-	-	2.20	-1.91	-	-
Change/unit of porosity						
Historic flows	0.03	-	-	-	0.09	1.3
Historic + prehistoric	0.20	-	1.83	-	0.17	-
Change/% of Ca+Na content						
Historic flows	-	-	-	-	0.16	-
Historic + prehistoric	0.16	0.17	-	-4.6	0.22	-

* pH units

** As % of amount originally present

*** Cubic decimeters

losses of rocks under trees and those on bare lava on the 1750 flow (Table XX). The large loss of sodium from rocks among roots as compared to those in a protected position underneath the trunk (Table XXI) may also indicate that plant litter has a considerable effect on weathering. Here, however, some of the rocks under trunks may be almost completely protected from leaching. Taken as a whole, the data lends some support to the assumption that the effective plant factor, as defined in this study (p. 125), is measuring a factor of significance to weathering.

Rates of Succession

Consideration can now be given to the question of overall rates of change i.e. the resultant rates of change when all ecosystem factors are included. Because of the number of factors influencing rates, generalizations are not readily made. In Table XXXI rates of change, based on sample averages, have been summarized for the three major climatic zones of the study area. Rainfall in the coastal zone is 115 inches, that in the low-altitude zone varies from 110 to 140 inches, and rainfall in the mid-altitude zone covers the range 140 to 210 inches. Mean annual temperatures vary from 73°F. at the coast to 60°F. at 3800 feet. The figures for the coastal zone are from the 1840L site alone, since the estimated age of the prehistoric Kapoho flow is too uncertain. The low-altitude rates are means derived from the 1840H, 1750H and Lower Stainback sites. Figures for the mid-altitude zone are from the 1852 and Upper Stainback measurements. An age of 360 years is assumed for both the Upper and Lower Stainback flows (see Age Determinations). The results for both these flows are shown separately since they may give a more representative figure for average rates of change during the first 400 years of ecosystem development.

TABLE XXXI. RATES OF CHANGE OF WEATHERED ROCK AND VEGETATION PARAMETERS ON SELECTED LAVA FLOWS

Parameter	AA FLOWS					PAHOEHOE	
	Coastal Zone 40 ft.	Low-Alt. Zone 300-1000 ft.		Mid-Alt. Zone 3600-3800 ft.		Low-Alt.	Mid-Alt.
	1840L	Mean 3 Flows	Lr. Stbk.	Mean 2 Flows	Upr. Stbk.	Samoa 1760	1855
ΔpH (pH units/ century)	0.13	0.30	0.19	0.28	0.23	0.39	0.75
pHc "	0.76	1.50	0.98	1.37	0.95	0.53	2.55
Na loss (% o.d.wt./ century)	N.S.	0.14	0.15	0.28	0.34	N.S.	N.S.
Ca loss "	N.S.	0.20	0.26	0.36	0.39	N.S.	0.22
Ti gain "	0.07	0.05	0.13	0.10	0.18	-	-
Si loss "	-	-	-	1.29	1.29	-	-
K loss "	-	-	-	-	0.01	-	-
Mg gain "	-	-	-	-	0.29	-	-
Weight loss %	0.60	0.90	0.80	0.85	0.90	0.20	0.80
Tree vol. estimate (cub. dm/cent.)	15.3	1772*	(250)	198	394	-	0.5
Height growth (meters/cent.)	2.7	7.7*	(5.0)	3.8	5.6	-	1.9
Stratum depth (meters/cent.)	2.3	4.1	(4.1)	3.6	4.4	-	2.0

* Means for 1840H and 1750H sites only.

Since the amount of floristic difference between flows of differing age is not very great (Appendix III), rates of succession on the flows studied are best examined in terms of structural change.

Considering first the early stages of succession, rates of lichen cover were calculated by dividing the transect percentages for lichen cover by the age of the flow. The results for an open site in each of the three zones were:

Coastal (1840L: 40 ft. alt.) ......0.3% per year
Low-altitude (1955 : 990 ft. alt.) ......6.2% per year
Mid-altitude (1942 : 3720 ft. alt.) ......2.3% per year

Both the 1955 and the 1942 sites have higher than average rock porosities, so that the rates of lichen cover measured here may be faster than usual.

Rates of change for later stages of succession are included in Table XXXI. Since the *Metrosideros* forest of the Lower Stainback site is probably secondary, the vegetation and organic horizon measurements for this site have been enclosed in brackets. Excluding this site, it can be seen that tree volume estimates, height growth and total stratum depth all show higher rates of change in the low-altitude zone. A specific comparison can be made between the low-altitude 1840H site with a rate of tree-volume increase of 82.7 cubic decimeters per century, and the mid-altitude 1852 site with a rate of only 2.46 cubic decimeters per century.

Although there are insufficient sites to give precise times for stages of succession, a general statement is possible. It seems probable that on aa flows in a mid-altitude zone having a humid climate and a mean annual temperature of 60°F., forest (80% or more canopy cover of trees) is developed within 300 years of flow formation. At lower altitudes

(c. 70°F.) forest can develop within 200 years, provided the climate is generally humid rather than having frequent summer-dry periods.

These rates are slower than those recorded for Krakatoa by Richards (1952) and by Tagawa (1964) for Sakurajima, Japan. However, neither case is really comparable to the Hawaiian flows studied, since both the Krakatoa and Sakurajima flows were covered by pumice.

It may be pointed out that these rates of forest development are almost certainly not the maximum rates of Metrosideros succession that can occur on ash-free lava flows in Hawaii. General observations in the Honaunau district (Kona) indicate that climatic conditions there may be nearer the optimum for Metrosideros growth. If a figure of approximately 250 years is taken as the age of the Honaunau site (Table XXVII), this gives a rate of tree-volume increase of 1,640 cubic decimeters per century. This site is at 3,250 feet, so that the rate of development may be considerably higher at lower altitudes, if summer-dry conditions are not dominating.

More data are needed from pahoehoe flows in humid areas but some comparison with succession on aa flows is possible. Vegetation parameters measured on the Mauna Loa 1852 aa and 1855 pahoehoe sites, and similarly on the 1840H aa and 1793 pahoehoe sites of Kilauea (Tables VIII and XXIII), show that vegetation succession is more rapid on the aa flows (cf. Forbes 1912). However, as cautioned by Skottsberg (1941), pahoehoe varies a great deal with regard to hardness and frequency of cracks, so that it cannot be assumed that weathering and plant succession will always be slower.

Rates of Weathering

In Table XXXI the weathered rock measurements for the 1955 and 1942 flows were excluded because, in both cases, rates of change appear to be faster than usual. These high rates of change may be related to high porosity and weak particle coherence, mentioned earlier. They may also be a result of rapid initial rates of release from weathering minerals as found by McClelland (1950) in laboratory experiments.

Rates of change for weathering parameters (Table XXXI) show definite differences between the climatic zones distinguished. However, the weight-loss measurements, apart from two sites where summer-dry conditions prevail (1840L and Samoa 1760), show a very consistant rate of change of 0.8 to 0.9% per century.

Although there are data from only one coastal site (1840L), the changes are generally slower than in the inland wetter districts. Rates of change in pH are highest in the low-altitude zone whereas the rates for sodium loss, calcium loss and titanium gain tend to be highest in the mid-altitude zone where rainfall is highest. Hough, Gile and Foster (1941) and Tanada (1951) found that titanium accumulation increased with increasing rainfall.

Assuming the Lower and Upper Stainback sites to be of similar age (c. 360 years), a direct comparison can be made in rates of weathering at the two altitudes (300 and 3660 feet). Rainfall is similar (140 inches) but mean annual temperatures differ by approximately 12°F. There is little difference in the pH measurements but rates of sodium and calcium loss, titanium gain and the weight-loss measurement are all greater at the higher altitude. So far as elemental changes are concerned, these measurements indicate that weathering is more rapid at mid-altitudes than at lower levels.

An explanation for these observations may lie in the development of a relatively deep organic horizon (16.5 cm) at mid-altitudes. As discussed in the results, this can probably be related to decreased decomposition rates associated with the decreased temperature. With accumulation of an organic horizon there would be many changes in the micro-environment of a weathering rock. Evaporation would be reduced so that surface rocks would be permanently moist. Acid plant litters would acidify the water moving through the profile. pH measurements of the organic horizon on the 1852 and Upper Stainback sites gave values ranging from 3.8 to 4.5 . The solubility of aluminum increases very rapidly below a pH of 4.5 (Correns 1949, Krauskopf 1959) and this is perhaps why it was not possible to demonstrate a significant concentration of aluminum in rocks from the Upper Stainback site (Table XIV). The 1852 flow with an organic horizon averaging nearly 12 cm in depth (Table IX) actually showed a loss of aluminum (Table XIV).

Data for weathered rock parameters from the pahoehoe samples is insufficient to allow a proper comparison with aa flows. However the pH measurements show that rates of change are not always slower on pahoehoe flows.

A further important question concerns the manner in which the rate of weathering can change with time. The summation of the rates of change per century for each of the parameters: ΔpH, pHc, Na loss, Ca loss, Ti gain and 110-350°C. weight loss, can be used as an index of the overall rate of weathering. The indices for 4 flows in the low-altitude range (300 to 1000 feet) are:

1955	1840H	1750H	Lower Stainback
27.53	3.77	2.92	2.51

Even though the rate of weathering of the 1955 rocks may be higher than usual, the trend in the above figures is clear: a decreasing weathering rate with increasing time. When plotted, these figures approximate to a negative exponential function.

Two reasons for this trend can be suggested. Following development of a closed vegetation cover, microclimate conditions would be subject to much less fluctuation than during earlier stages of weathering. Secondly, McClelland (1950) investigated mineral weathering under laboratory conditions and found that while bases were released from fresh minerals at a fast rate, it appeared that with increasing time, residual primary weathering products were retarding the release of bases from the minerals.

Relationship between Succession and Weathering on Hawaiian Lava Flows

It is sometimes considered that soil and vegetation development are so closely related, that the stage reached by one process, will parallel the stage reached by the other. However, even allowing the close connection between the two processes brought about by biocycling of minerals, it seems unwise to correlate soil and vegetation development on lava flows too closely. A fully developed forest can occur on a flow where, although there has been some weathering, the formation of mineral or organic soil material is negligible, e.g. the 1750H site.

The results from this study show that while the rate of succession is highest at low elevations, the rate of rock weathering and development of an organic horizon is highest at mid-altitudes. In this whole region of relatively high rainfall, it is considered that temperature is the differentiating factor. The higher temperatures at low altitudes increase the rate of plant growth and reduce the rate of leaching, and therefore weathering, by increasing evaporation. The lower temperatures at middle altitudes decrease plant growth and facilitate weathering by increasing the accumulation of organic matter.

Importance of the Stainback Flows as a Study Area

The Stainback Highway stretches for 19 miles from the Volcano Highway (280 feet) up the slopes of Mauna Loa to the Kulani prison (c. 4700 feet). The area was originally completely covered in thick forest; extensive stands of Metrosideros forest are still present on both sides of the road for the greater part of its length. The detailed land classification for Hawaii (Baker et al, 1965) shows several soil boundaries crossing the Stainback road. This would imply that the road crossed several old flows. However, after a preliminary reconnaissance of the area, it was considered possible that this flow might be continuous all the way from below the junction of the Stainback road with the Volcano Highway up to an altitude of about 4600 feet. At this elevation it is overlain by a more recent prehistoric flow.

The rock analyses of the unweathered rocks from the Upper and Lower Stainback sites, are consistent with the idea of these sites being on the same flow or on very similar flows:

	pH_{H_2O}	Na_2O%	CaO%	TiO_2%	Wt-loss %
Upper Stainback (3780 feet)	9.37	2.53	9.77	2.13	0.09
Lower Stainback (300 feet)	9.35	2.23	9.72	1.83	0.24

The differences between these two analyses are within the range of sample variation that can be found on a single flow (see Results). The largest difference, that of titanium content, may be the result of gravitative differentiation in the magma reservoir before eruption. Macdonald (1944) describes a case of gravitative crystal differentiation in the 1840 eruption of Kilauea where the iron content of the groundmass (determined by optical measurement) was 7% lower in the flows near sea-level than that of later flows produced at higher levels. Since titanium is associated with iron oxides, it could be expected that the earlier erupted, lower part of a flow, would have a lower titanium content.

The age determinations from Equations 1 and 2 suggest that the two Stainback sites, if not on the same flow, are on flows little different in age. Age calculations from three other regression equations, with R^2 values less than that of Equation 1 (65-75%), gave ages for the two sites that ranged from 308 to 347 years. However these equations were consistent in giving a slightly younger age (10 to 39 years) to the Lower Stainback site.

If this hypothesis of similar age for the two Stainback sites is substantiated, there are good opportunities here to make further comparisons of rates of development at different altitudes. Since most of the ecosystem factors, particularly rainfall, are similar, differences in rates of weathering, leaching, clay formation and other processes can be related to differing temperature and possibly disturbance factors that have affected the vegetation.

The boundaries of the Stainback flow (or flows) are not known, but the flow is probably represented for some distance at higher and lower altitudes than those sampled. Lobes of adjacent flows may cross the road in some places. If the pattern of flows in this district can be mapped, much more could be learnt from comparisons between different altitudes and between adjacent flows. For example, koa (Acacia koa) occurs on what is presumably an older flow immediately to the north of the main Stainback flow. This species was not seen nearer the highway except as planted trees.

Detailed mapping of contours, using aerial photograph techniques, together with field mapping of the vegetation, using both understorey and overstorey composition, may be the easiest way to distinguish separate flows. The following points may help future investigators:

1. In some places the Stainback flow grades into "semi-pahoehoe" and then back to aa again. This "semi-pahoehoe" surface is associated with shallower depths in the organic horizon and Metrosideros forest of lower density than typical of the aa surface. Such variation can mislead one into thinking that another flow has been encountered.

2. Disturbance of the original forest, apparently by fire as well as cutting, is more marked below 1800 feet than above this altitude. This disturbance pattern is superimposed on gradients of increasing forest height, tree diameter and species diversity that are associated with the zone of highest rainfall between 1500 and 3000 feet.

Apart from particular studies of the vegetation and rock weathering that could be made, the Stainback area appears to be a suitable location for study of the genesis of tropical histosols. No attempt was made to classify the organic soils present but auger borings made at different altitudes showed that few of these soils would meet the depth requirement of a typic folist. A class such as "lithic tropofolist" may be needed.

The flows of the Stainback area are only part of a soil-vegetation sequence that extends from sea-level to 13000 feet. This sequence is unique both floristically and faunistically and though damaged or destroyed in places, there can be few places in the Pacific region where such a complete sequence can still be studied. There is thus ample reason for permanently reserving representative areas of 5 to 10 acres at intervals of 300 to 500 feet altitude from the shoreline to the summit of Mauna Loa.

Aging a Lava-Flow Ecosystem

In using parameters of weathered rock to age lava-flow ecosystems, there are two main limitations to be overcome. The first is to find a method of sampling the flow in a representative and reproducible manner. The second is to find a rock parameter that changes with time in a predictable manner. If the parameter is dependent on rainfall and temperature, the effects of these factors can be measured. Ideally, the parameter should be little influenced by differences in rock composition, porosity and texture within the one type of lava, e.g. olivine basalt.

Considering the sampling problem, it can be seen from the earlier discussions that there was sometimes doubt concerning the degree of weathering of the 'unweathered' samples, particularly on older flows. This problem of a shifting baseline in the 'unweathered' rock could cause considerable error if an attempt was made to age flows older than the 400 year period covered in this study. If a particular parameter of unweathered rock of a given composition was found to be relatively constant between flows, then this could be taken as a baseline. This would overcome the difficulty of obtaining accurate measurements for unweathered rocks on every flow sampled.

In this study the 110-350°C. weight loss and the pHc measurements approach the idealized situation described above more closely than the other parameters measured. With some refinements to the weight-loss measurement, (e.g. rigid control over particle size during grinding), it may be possible to increase the precision of this measurement. By experimenting with temperatures above and below 350°C., a temperature level might be found at which the weight-loss of an unweathered sample was nearly constant for a given range of rock composition. The weight losses of unweathered rocks at this temperature would then be a measure of the degree of weathering and could be used as an age index as was done in this study. Judging by the results obtained here, hydrolysis and hydration of rocks, as measured by weight-loss, are more influenced by effective rainfall than other factors. This is a further advantage as pointed out above.

Attention could also be given to studying the factors that influence rock pH. It seems likely that the pH values for unweathered basalts fall within a narrow range (Table **X**). Thus the pH_{H_2O} or pH_{KCl} value of unweathered rocks, can possibly be used as an accurate measurement of the degree of weathering; measurements of large numbers of unweathered samples would again be unnecessary.

Data for pahoehoe flows were insufficient to allow use of regression analyses for aging purposes. However, the magnitude of both the weight-loss and the pH measurements for pahoehoe rocks was larger than expected. It now seems that with further study it may be possible to develop methods for aging pahoehoe flows.

There are other lines of attack on the general problem of aging that could be pursued. One approach would be to apply the principle used in dating with radioactive isotopes. The amount of parent isotope decreases continually as it changes to the daughter isotope. The daughter isotope is stable and is retained in the rock so that the total amount of change can be measured. In the absence of suitable isotopic pairs, the next choice would be an element which is slowly changed to a rather insoluble compound, that is retained within the fabric of the weathering rock. For example, Nakamura and Sherman (1961) found that vanadium accumulates in Hawaiian soils in sufficient amounts to make it potentially useful as a weathering index. This element is probably present in magmas as the V^{3+} ion (Mason 1966) and is associated with pyroxenes and magnetite (Wager and Mitchell 1951). If vanadates can be determined separately from elemental vanadium, a ratio of total vanadium (all oxidation states) to vanadate ion (V^{5+}) could be useful as an age index. The molybdenum/molybdate ratio may also be worth examining from the same point of view. Here, however, the total amounts present are sometimes less than 1 ppm (Wager and Mitchell 1953) as compared to 100 - 400 ppm for vanadium (Nakamura and Sherman, loc. cit.).

The regression equations of the present study give a quantitative description of the effects of various environmental factors on weathering although they do not provide mathematical models for the processes operating. Thus Equation 2 (see Age Determinations) states that weight loss is a function of time, temperature and rainfall. This rather simple equation could be used as a starting point for a more general equation that was applicable to a wider range of conditions. By taking one of the older dated flows and sampling a weathering parameter through the full range of site conditions present, it should be possible to get sufficient information to build some general equations.

An assumption made in the age determinations is that of climatic stability throughout the period for which age extrapolation has been made. There is good evidence that this is not so even during the last 400 years. Thus, on a world basis, Lamb and Johnson (1961) summarize evidence for a "Little Ice Age" that culminated in the 1600's. In Hawaii, Selling (1948) gives pollen evidence for climatic deterioration about 1200 A.D. although here the possibility must be considered that the changes in pollen frequency are related to forest destruction by the early Hawaiians.

In the present case, error arising from climatic change is probably minor. Equation 1 does not utilize measurements of current climatic variables but rather calcium and sodium losses which would integrate the leaching effect of past climate. This equation may be invalid in climates beyond the range of climatic data from which it was built. Equation 2 is dependent on current rainfall and temperature measurements at the site being representative of the past climate, and is therefore more vulnerable to error due to climatic change. However the measurements for the effects of rainfall and temperature on weight loss (Table XXX) indicate that climatic change would have to be considerable before large errors could be expected.

As more information on past climates becomes available it should be possible to correct for these changes by using information of the type recorded in Table XXX. Within the climatic range studied, the measured effects on pHc or weight loss of a 10 inch change in rainfall are not large.

The aging methods developed in this study can be used for assigning relative ages to lava-flow ecosystems within the limits of the confidence intervals. It would be interesting to see how the dating of some lava flows by the methods of this study compares with carbon-dating. Approximately two to three hundred grams of carbonaceous material is needed in order to age a 300-400 year lava flow with a possible error of ± 50 years. The methods of this study may prove to be very useful in indicating the ages of lava-flow ecosystems, particularly in cases where carbonaceous material cannot be found.

SUMMARY OF CONCLUSIONS

1. With the aid of regression analysis and inverse estimations from dated lava flows, it is possible to use measurements of the weathered rock to obtain meaningful ages for previously undated prehistoric aa flows in the age range 200 to 400 years B.P. and rainfall range of 90 to 150 inches per annum. With further study this time span and climatic range could probably be extended.

2. Study of successional trends in this high-rainfall region shows that during the first 200 years of succession the main colonizing tree species, Metrosideros polymorpha, first increases and then decreases in numbers. With decrease in numbers it is partly replaced by several species of trees, e.g. Pandanus tectorius, Diospyros ferrea and Cibotium tree-ferns depending on available moisture and position relative to the coastline.

3. There is little difference between successional trends on aa and pahoehoe flows in the climatic region studied.

4. Rates of succession in this high-rainfall region are very variable. At altitudes below 1000 feet and at mean annual temperatures of about 70°F., forest can develop within 200 years. At 60°F. mean annual temperature (3000 to 4000 feet) forest can develop within 300 years of flow formation.

5. The main factor determining the rate of plant succession appears to be available moisture as governed by rainfall, temperature, inter-rock porosity (i.e. size distribution of rocks and the frequency of crevices), and the porosity of individual rocks.

6. Weathering trends in the young rocks analysed ($<$ 400 years old) are similar to those described in the literature for more weathered

rocks. The regression analysis shows that climatic factors, plant factors and physical and chemical properties of the weathering rock are all influencing the rate of weathering with no one factor being dominant.

7. Rates of rock weathering for the 400 year period studied were as follows: pH changes of 0.76 to 1.50 pH units per century, sodium loss of $< 0.1 - 0.3\%$ per century, calcium loss of $< 0.1 - 0.4\%$ per century, relative titanium gain of 0.05 - 0.18% per century, and gain in water of 0.6 - 0.9% per century.

8. Rates of rock weathering are decreasing with increasing time.

9. In this high-rainfall region, the most important effect of higher temperatures is in increasing evaporation and thus decreasing leaching, rather than in increasing the rate of chemical reactions.

10. Evidence from comparisons on the same flow and from the regression analysis of the data from all flows, indicates that plants can have a significant weathering effect, particularly on rates of sodium loss.

11. In this high-rainfall region, the rate of succession is highest at altitudes below 1000 feet whereas the rate of rock weathering, at least as far as elemental changes are concerned, is greater between 3000 and 4000 feet. Temperature, with its effects on plant growth, evaporation and accumulation of organic matter, appears to be the differentiating factor.

12. There is an unusually good opportunity to study processes of succession and weathering in a wide range of climates by using the sequence of soils and vegetation that extends from sea-level to the summit of Mauna Loa in the Stainback highway region. For this reason

it is considered that a series of representative areas in this sequence should be permanently reserved for future study.

LITERATURE CITED

Baker, H.L., T. Sahara, T.M. Ryan, E.T. Murabayashi, A.Y. Ching, F.N. Fujimura and I. Kuwahara. 1965. Detailed land classification - Island of Hawaii. Land Study Bulletin No. 6, Land Study Bureau, University of Hawaii, Honolulu, Hawaii.

Bardossy, G. and M. Bod. 1961. A new method to characterize the state of oxidation of rocks. Acta Geologica 7: 29 - 35.

Barton, D.C. 1916. Notes on the disintegration of granite in Egypt. J. Geol. 24: 382 - 393.

Bates, T.F. 1960. A mineralogical study of parent rock to clay mineral alteration in the Hawaiian Islands. Dept. of Mineralogy, College of Mineral Industries, Penn. State University.

Beschel, R.E. 1961. Dating rock surfaces by lichen growth and its application to glaciology and physiography (lichenometry). In Raash, G.O. (ed.), Geology of the Arctic. Univ. Toronto Press, Toronto, v. 2: 1044 - 1062.

Blake, G.R. 1965. Bulk density. In Black, C.A. (Ed.). Methods of Soil Analysis. Pt. 1, Chap. 30. American Soc. Agron. Monog. No. 9.

Blumenstock, D.I. and Saul Price. 1967. Climates of the States. Hawaii. Climatography of the United States No. 60-51, U.S. Dept. of Commerce, Washington.

Burges, A. and D.P. Drover. 1953. The rate of podzol development in the sands of the Woy Woy district, New South Wales. Aust. J. Bot. 1: 83 - 94.

Campbell, C.A., E.A. Paul, D.A. Rennie and K.J. McCallum. 1967. Applicability of the carbon-dating method of analysis to soil humus studies. Soil Sci. 104: 217 - 224.

Champion, K.P., J.C. Taylor and R.N. Whitten. 1966. Rapid X-ray fluorescence determinations of traces of strontium in samples of biological and geological origin. Anal. Chem. 38 (1): 109 - 112.

Chandler, R.F. 1942. The time required for podzol profile formation as evidenced by the Mendenhall glacial deposits near Juneau, Alaska. Soil Sci. Soc. Amer. Proc. 7: 454 - 459.

Cline, M.G. 1955. Soil Survey of the Territory of Hawaii. U.S. Dept. of Agric. Soil Survey Series 1939, No. 25.

Correns, D.W. 1949. Einfuhrung in die Mineralogie, Springer-Verlag, Berlin.

Crocker, R.L. 1952. Soil genesis and the pedogenic factors. Quart. Rev. Biol. 27: 139 - 168.

Crocker, R.L. and B.A. Dickson. 1957. Soil development on the recessional moraines of the Herbert and Mendenhall glaciers, Southeastern Alaska. J. Ecol. 45: 169 - 185.

Crocker, R.L. and J. Major. 1955. Soil development in relation to vegetation and surface age at Glacier Bay, Alaska. J. Ecol. 43: 427 - 448.

Cross, Whitman. 1915. Lavas of Hawaii and their relations. U.S. Geol. Surv. Pap. 88.

Daly, R.A. 1911. Magmatic differentiation in Hawaii. J. Geol. 19: 289 - 316.

Dickson, B.A. and R.L. Crocker. 1953. A chronosequence of soils and vegetation near Mt. Shasta, California. J. Soil Sci. 4: 123 - 154.

Doell, R.R., and A. Cox. 1961. Palaeomagnetism of Hawaiian lava flows. Nature 192: 645 - 646.

Doty, M.S. 1961. Lava flow pioneer populations. In Fosberg, F.R. (prep. by) Guide to Excursion III, pp. 139 - 146. Tenth Pac. Sci. Cong. and Univ. of Hawaii.

__________ 1967. Contrast between the pioneer populating process on land and shore. Bull. Southern Calif. Acad. of Sci. 66: 175 - 194.

Doty, M.S., and D. Mueller-Dombois. 1966. Atlas for Bioecology Studies in Hawaii Volcanoes National Park. Hawaii Botanical Science Paper No. 2. University of Hawaii.

Druce, A.P. 1966. Tree-ring dating of recent volcanic ash and lapilli, Mt. Egmont. New Zealand Jl. Bot. 4: 3 - 41.

Eggler, W.A. 1967. Influence of volcanic eruptions on xylem growth patterns. Ecology 48: 644 - 647.

Efroymson, M.A. 1960. "Multiple Regression Analysis" in Ralston, A. and H.S. Wilf (Ed.). Mathematical Methods for Digital Computers, Pt V. Chap. 17.

Esekiel, M., and K.A. Fox. 1959. Methods of Correlation and Regression Analysis. 3rd Ed. John Wiley and Sons, Inc.

Fergusson, G.J., and T.A. Rafter. 1957. New Zealand ^{14}C age measurements - 3. New Zealand J. Sci. Tech. B.38: 732 - 749.

Forbes, C.N. 1912. Preliminary observations concerning the plant invasion on some of the lava flows of Mauna Loa, Hawaii. Bernice P. Bishop Mus., Occ. Papers 5 (1): 15 - 23.

Fosberg, F.R. (prep. by) 1961. Guide to Excursion III, Tenth Pacific Science Congress. Tenth Pac. Sci. Cong. and Univ. of Hawaii.

Frazer, G.D. 1960. Pahala Ash - an unusual deposit from Kilauea Volcano, Hawaii. U.S. Geol. Surv. Prof. Pap. 400: B - 354 -5.

Friedman, I. 1968. Hydration rind dates rhyolite flows. Science 159: 878 - 880.

Gilliard, T. Unpbl. Identification and characterization of clay mineral species in soils of the western region W-87. Unpub. rept. to Dept. of Agronomy and Soil Science, University of Hawaii.

Goldich, S.S. 1938. A study in rock-weathering. J. Geol. 46: 17 - 58.

Grant, W.H. 1963. Weathering of Stone Mountain granite. Clays and Clay Minerals. Proc. Eleventh National Conf. on clays and clay minerals: 65 - 73.

Harrison, J.B. 1934. The katamorphism of igneous rocks under humid tropical conditions. Imp. Bur. Soil Sci. (Harpenden), pp 79.

Hawaii Institute of Geophysics Interlaboratory Standards. Unpubl. analyses by Japan Anal. Chem. Res. Inst. Rept. JAC 6525 and U.S. Geological Survey Lab. Rept. 66DC-7.

Hendricks, D.M. and L.D. Whittig. 1968. Andesite weathering II. Geochemical changes from andesite to saprolites. J. Soil Sci. 19: 147 - 153.

Hitchcock, C.H. 1911. Hawaii and its volcanoes, 2nd ed. The Hawaiian Gazette Co. Honolulu.

Hough, G.J., P.L. Gile and Z.C. Foster. 1941. Rock weathering and soil profile development in the Hawaiian Islands. U.S. Dept. Agri. Tech. Bull. 752.

Hsu, P.H. 1963. Effect of initial pH, phosphate, and silicate on the determination of aluminum with aluminon. Soil Sci. 96: 230 - 238.

Jackson, M.L. 1956. Soil Chemical Analysis - Advanced Course. (Third Printing, 1967). Publ. by the author, Dept. Soil Sci. University of Wisconsin, Madison, Wisconsin.

____________ 1958. Soil Chemical Analysis. Prentice-Hall.

Jenny, H. 1931. Soil organic matter-temperature relationships in the eastern United States. Soil Sci. 31: 247 -252.

________ 1941. Factors of Soil Formation, a system of quantitative pedology. McGraw-Hill Book Co. Inc. New York.

________ 1958. Role of the plant factor in the pedogenic functions. Ecology 39: 5 - 16.

________ 1961. Derivation of state factor equations of soils and ecosystems. Soil Sci. Soc. Amer. Proc. 25: 385 - 388.

Jenny, H., S.P. Gessel and F.T. Bingham. 1949. Comparative study of decomposition rates of organic matter in temperate and tropical regions. Soil Sci. 68: 419 - 432.

Julian, P.R. and H.C. Fritts. 1968. On the possibility of quantitatively extending climatic records by means of dendroclimatological analysis. Proc. 1st Statistical Meteorological Conf., Connecticut. Amer. Met. Soc.

Kear, D. and B.L. Wood. 1959. The Geology and Hydrology of Western Samoa. New Zealand Geol. Surv. Bull. 63.

Kelly, W.C. and J.H. Zumberge. 1961. Weathering of a quartz diorite at Marble Point, McMurdo Sound, Antarctica. J. Geol. 69: 433 - 446.

Kelley, W.P., H. Jenny and S.M. Brown. 1936. Hydration of minerals and soil colloids in relation to crystal structure. Soil Sci. 41: 259 - 274.

Kosaka, J. 1963. Division of the process of humification in upland soils, and its application to soil classification. Soil Sci. and Pl. Nutr. 9: 14 - 18.

Krajina, V.J. 1963. Biogeoclimatic zones on the Hawaiian Islands. Newsletter of the Hawaiian Botanical Society 2 (7): 93 - 98.

Krauskopf, K.B. 1959. The geochemistry of silica in sedimentary environments: silica in sediments. Soc. Economic Palae. and Min. Symposium 7: 4 - 18.

Krutchkoff, R.G. 1967. Classical and inverse regression methods of calibration. Technometrics 9: 425 - 439.

Lamb, H.H. and A.I. Johnson. 1961. Climatic variation and observed changes in the general circulation. Geografiska Annaler 43: 363 - 400.

Lawrence, D.B. 1950. Estimating dates of recent glacier advances and recession rates by studying tree growth layers. Trans. Am. Geophys. Union 31: 243 - 248.

__________ 1954. Diagrammatic history of the northeast slope of Mt. St. Helens, Washington. Mazama 36: 41 - 44 (Portland, Oregon).

MacCaughey, V. 1917. Vegetation of Hawaiian lava flows. Bot. Gaz. 64: 386 - 420.

Macdonald, G.A. 1944. The 1840 eruption and crystal differentiation in the Kilauean magma column. Amer. J. Sci. 242: 177 - 189.

__________ 1949a. Petrography of the Island of Hawaii. U.S. Geol. Surv. Prof. Pap. 214-D.

__________ 1949b. Hawaiian Petrographic Province. Bull. Geol. Soc. Amer. 60: 1541 - 1596.

Macdonald, G.A. and J.P. Eaton. 1964. Hawaiian volcanoes during 1955. U.S. Geol. Surv. Bull. 1171: 156 - 157.

Macdonald, G.A. and T. Katsura. 1962. Relationship of Petrographic Suites in Hawaii. Amer. Geoph. Un. Monog. 6: 187 - 195.

__________ __________ 1964. Chemical composition of Hawaiian Lavas. J. Petrol. 5: 82 - 133.

Mason, B. 1966. Principles of Geochemistry (Third Ed.). John Wiley and Sons.

Matsusaka, Y., G.D. Sherman, and L.D. Swindale. 1964. Nature of magnetic minerals in Hawaiian soils. Soil Sci. 100: 192 - 199.

McClelland, J.E. 1950. The effect of time, temperature, and particle size on the release of bases from some common soil-forming minerals of different crystal structure. Soil Sci. Soc. Amer. Proc. 15: 301 - 307.

McGeorge, W.T. 1917. Composition of Hawaiian soil particles. Hawaii Agric. Expt. Sta. Bull. 42.

Montagne, Hebel W. Unpbl. Unpubl. rept. to Dept. Agronomy and Soil Science, University of Hawaii.

Mordy, W.A. 1957. Geographic and Climatic notes on the Project Shower area. Tellus 9: 472 - 474.

Morison, C.G.T., A.C. Hoyle and J.F. Hope-Simpson. 1948. Tropical soil-vegetation catenas and mosaics. J. Ecol. 36: 1 - 84.

Mueller-Dombois, D. 1966. The Vegetation Map and Vegetation Profiles. Chap. 8 <u>in</u> Doty, M.S. and D. Mueller-Dombois, Atlas for Bioecology Studies in Hawaii Volcanoes National Park. Hawaii Bot. Sci. Pap. No. 2. University of Hawaii.

Nakamura, M.T. and G.D. Sherman. 1961. The vanadium content of Hawaiian Island soils. Hawaii Agric. Expt. Stn. Tech. Bull. 45.

Newman, I.V. 1954. Locating strata in tropical rain forests. J. Ecol. 42: 218 - 219.

Olson, J.S. 1958. Rates of succession and soil changes on Southern Lake Michigan sand dunes. Bot. Gaz. 119: 125 - 170.

Perrin, R.M.S., E.H. Willis and C.A.H. Hodge. 1964. Dating of humus podzols by residual radiocarbon activity. Nature 202: 165 - 166.

Price, N.B. and G.R. Angell. 1968. Determination of minor elements in rocks by thin film X-ray fluorescence techniques. Anal. Chem. 40 (3): 660 - 663.

Price, P.B. and R.M. Walker. 1963. Fossil tracks of charged particles in micas and the age of minerals. J. Geophys. Res. 68: 4847 - 4862.

Polynov, B.B. 1937. The Cycle of Weathering. Transl. by A. Muir. Thomas Murby and Co., London.

Reiche, Parry. 1943. Graphic representation of chemical weathering. J. Sediment. Petrol. 13: 58 - 68.

Richards, P.W. 1952. The Tropical Rain Forest. Cambridge Univ. Press.

Robyns, W. and S.H. Lamb. 1939. Preliminary ecological survey of the Island of Hawaii. Bull. Jord. Bot. Brux 15: 241 - 293.

Rooksby, H.P. 1961. Oxides and hydroxides of aluminum and iron. Chap. X _in_ Brown, G. (Ed.). The X-ray Identification and Crystal Structure of Clay Minerals. Mineralogical Society, London.

Rubin, M. and S.M. Berthold. 1961. U.S. Geol. Survey radiocarbon dates VI. Radiocarbon 3: 86 - 98.

Ruxton, B.P. 1968. Rates of weathering of quaternary volcanic ash in North-east Papua. Trans. 9th Int. Cong. Soil Sci. 1968. Vol. IV: 367 - 376. Int. Soc. Soil Sci.

Sabels, B.E. 1963. Age studies on basaltic lava flows using natural alpha activity and thermoluminescence. _In_ Radioactive Dating. International Atomic Energy Agency, Vienna.

Salisbury, E.J. 1925. Note on the edaphic succession in some dune soils with special reference to the time factor. J. Ecol. 13: 322 - 328.

Selling, O.H. 1948. Studies in Hawaiian pollen statistics. Part III. On the late quaternary history of the Hawaiian vegetation. B.P. Bishop Museum Spec. Pub. 39.

Shapiro, L. and W.W. Brannock. 1962. Rapid analysis of silicate, carbonate and phosphate rocks. Geol. Surv. Bull. 1144 - A.

Sherman, G.D. and H. Ikawa. 1968. Soil sequences in the Hawaiian Islands. Pac. Sci. 22: 458 - 464.

Sherman, G.D. and Y. Kanehiro. 1948. The chemical composition of certain forest floors in the Hawaiian Islands. Biennial Report. University of Hawaii Agric. Expt. Stn. Honolulu, p. 54.

Sherman, G.D. and G. Uehara. 1956. The weathering of olivine basalt in Hawaii and its pedogenic significance. Soil Sci. Soc. Amer. Proc. 20: 337 - 340.

Skottsberg, C. 1941. Plant succession on recent lava flows in the Island of Hawaii. Gotteborgs Kungl Vetenskapoch Vitterhelssamhalles Handlinger Sjatte fojden, ser. B., Bd. 1, No. 8.

Smathers, G. 1966. Succession on new surfaces. In Atlas for Bio-ecology Studies in Hawaii Volcanoes National Park (pp 341 - 345) by M.S. Doty and D. Mueller-Dombois. Hawaii Bot. Sci. Paper No. 2 Univ. of Hawaii.

Smith, W.W. 1962. Weathering of some Scottish basic igneous rocks with reference to soil formation. J. Soil Sci. 13: 202 - 215.

Snedecor, G.W. 1956. Statistical Methods. Iowa State University Press.

Soil Survey Staff. 1951. Soil Survey Manual. U.S. Dept. Agriculture Handbook No. 18.

________________ 1968. Supplement to Soil Classification System (7th Approximation). Histosols. Soil Conservation Service, U.S. Dept. of Agriculture.

Stearns, H.T. 1966. Geology of the State of Hawaii. Pacific Books, Palo Alto, California.

Stearns, H.T. and G.A. Macdonald. 1946. Geology and Ground-water Resources of the Island of Hawaii. Bull. 9. Hawaii Division of Hydrography.

Stevens, R.E. and M.K. Carron. 1948. Simple field test for distinguishing minerals by abrasion pH. Am. Mineral. 33: 31 - 50.

Stork, A. 1963. Plant immigration in front of retreating glaciers, with examples from the Kebnekajse area, Northern Sweden. Geografiska Ann. 45: 1 - 22.

Suhr, N.H. and C.O. Ingamells. 1966. Solution technique for analysis of silicates. Anal. Chem. 38: 730 - 734.

Swindale, L.D. 1966. A mineralogical study of soils derived from basic and ultrabasic rocks in New Zealand. New Zealand Jl. Sci. 9: 484 - 506.

Swindale, L.D. and G. Uehara. 1966. Ionic relationships in the pedogenesis of Hawaiian soils. Soil Sci. Soc. Amer. Proc. 30: 726 - 730.

Tagawa, H. 1964. A study of the volcanic vegetation in Sakurajima, south-west Japan. I. Dynamics of vegetation. Memoirs of the Faculty of Science, Kyushu University, Series E (Biology) 3: 165 - 228.

Tanada, T. 1951. Certain properties of the inorganic colloidal fraction of Hawaiian soils. J. Soil Sci. 2: 83 - 96.

Tezuka, Y. 1961. Development of vegetation in relation to soil formation in the volcanic Island of Oshima, Izu, Japan. Jap. Jour. Bot. 17: 371 - 496.

Tiller, K.G. The geochemistry of basaltic materials and associated soils of south-eastern South Australia. J. Soil Sci. 9: 225 - 241.

Uehara, G., H. Ikawa and G.D. Sherman. 1966. Desilication of halloysite and its relation to gibbsite formation. Pacific Sci. 20: 119 - 124.

Volchok, H.L. and J.L. Kulp. 1957. The ionium method of age determination. Geochim. et Cosmochim. Acta 11: 219 - 246.

Viereck, L.A. 1966. Plant succession and soil development on gravel outwash of the Muldrow glacier, Alaska. Ecol. Monog. 36: 181 - 199.

Wager, L.R. and R.L. Mitchell. 1951. The distribution of trace elements during strong fractionation of basic magma - a further study of the Skaergaard intrusion, East Greenland. Geochim. et Cosmochim. Acta 1: 129 - 208.

__________ ____________ 1953. Trace elements in a suite of Hawaiian lavas. Geochim. et Cosmochim. Acta 3: 217 - 223.

Walker, T.W. 1964. The significance of phosphorus in pedogenesis. <u>In</u> Hallsworth, E.G. and D.V. Crawford (Ed.). Experimental Pedology, pp 295 - 316. Butterworths, London.

Wambeke, A.R. van 1962. Criteria for classifying tropical soils by age. J. Soil Sci. 13: 124 - 132.

Washington, H.S. 1923. Petrology of the Hawaiian Islands: II. Hualalai and Mauna Loa. Amer. J. Sci. 5th ser. 6: 100 - 126.

Weaver, K.F. 1967. Magnetic clues help date the past. Nat. Geog. 131 (5): 696 - 701.

Wells, N. 1960. Total elements in topsoils from igneous rocks: an extension of geochemistry. J. Soil Sci. 11: 409- 424.

Wentworth, C.K. 1938. Ash Formations on the Island of Hawaii. 3rd Spec. Rept. Hawaii Volcano Observatory, Honolulu.

Williams, E.J. 1959. Regression Analysis. John Wiley and Sons. New York.

____________ 1969. A note on regression methods in calibration. Technometrics 11: 189 - 192.

Wright, C.H. 1934. Soil Analysis. A Handbook of Physical and Chemical Methods.

APPENDIX I

PUBLISHED ANALYSES OF LAVA FLOWS SAMPLED IN STUDY

Element as Oxide	1840	1852	1881	1942	1955
SiO_2	47.25%	48.57%	52.65%	52.02%	51.06%
Al_2O_3	9.07	10.51	12.12	13.54	13.72
Fe_2O_3	1.45	2.19	2.19	5.25	2.44
FeO	10.41	9.45	8.87	6.58	10.34
CaO	7.88	8.06	10.12	10.23	9.46
MgO	19.96	17.53	7.43	7.31	5.44
TiO_2	1.61	1.48	3.52	2.09	3.65
Na_2O	1.38	1.59	2.25	2.30	2.62
K_2O	0.35	0.34	0.35	0.41	0.76
P_2O_5	0.21	0.19	0.25	0.27	0.39
MnO	0.13	0.16	0.11	0.09	0.18
H_2O +	0.04	0.37	0.24	0.06	0.12

1840 ... Picrite-basalt, Kilauea 1840 lava flow at Nanawale Bay, Puna district (Cross 1915).

1852 ... Picrite-basalt, Mauna Loa 1852 flow (Daly 1911).

1881 ... Hypersthene-bearing basalt, Mauna Loa 1880-81 flow near Hilo (Washington 1923).

1942 ... Basalt, earliest lava of 9200' vent of Mauna Loa 1942 flow, 0.4 miles west of main cone (Macdonald 1949b).

1955 ... Basalt, Kilauea lava flow from westernmost vents, erupted Mar. 20, 1955. Collected at Pahoa-Kalapana road 5 miles south of Pahoa, east Puna (Macdonald and Eaton 1964).

Note: These figures are analyses from particular parts of the flows that interested the investigator. They are not necessarily representative of the composition of the flow as a whole.

APPENDIX II

DATA FOR SITE FACTORS AND TIME USED IN THE REGRESSION EQUATIONS

Flow	Rainfall (in.)	Temp. °F.	Effective Plants	Rock Porosity	Rock Texture	Titanium Content %	Ca + Na Content %	Age (years)
1955	100	69.9	0.0	4.88	9.0	3.84	12.39	13
1942	150	60.2	0.0	2.50	9.6	2.09	12.82	26
1852	210	60.4	5.7	2.60	4.2	1.74	9.77	116
1840H	130	70.9	7.7	6.62	7.2	1.73	8.83	128
1840L	115	73.1	4.5	4.40	7.2	1.85	9.01	128
1750H	110	69.7	8.8	3.85	9.3	2.87	12.74	218
1750L	90	72.1	7.5	4.0	10.0	2.79	12.67	218
Upr. Stainback	140	60.0	9.9	3.95	7.2	2.13	12.30	?
Lwr. Stainback	140	72.1	9.7	2.90	7.2	1.83	11.95	?
Honaunau	88	61.8	9.7	2.67	9.0	2.13	14.15	?

APPENDIX III

LIST OF PLANTS FOUND ON SAMPLING SITES

Note: Lower plants are not recorded excepting Stereocaulon vulcani and Rhacomitrium lanuginosum..

(X) = introduced species

	1840L	Kapoho	1955	1840H	1750L	1750H	Lr. Stbk.	1942	1881	1855	1852	Upr. Stbk.
PTERIDOPHYTA:ASPIDIACEAE												
Cyclosorus parasiticus (L.)Farwell						+						
C. sandwichensis (Brack.) Copel.												+
C. truncatus (Poir.) Farwell		+										
ASPLENIACEAE												
Asplenium nidus L.		+				+						
Asplenium sp.		+		+				+				
BLECHNACEAE												
Sadleria cyatheoides Kaulf.	+			+	+			+	+	+	+	
DAVALLIACEAE												
Nephrolepis ?exaltata(L.)Schott								+	+	+	+	
N. hirsutula (Forst.f.) Presl (X)	+	+	+	+	+	+	+					
GLEICHENIACEAE												
Dicranopteris linearis (Burm.) Underwood				+	+				+	+	+	
HYMENOPHYLLACEAE												
Vandenboschia cyrtotheca (Hilleb.) Copel.						+	+					
LYCOPODIACEAE												
Lycopodium cernuum L.				+				+	+	+	+	

APPENDIX III (Continued). LIST OF PLANTS FOUND ON SAMPLING SITES

	1840L	Kapoho	1955	1840H	1750L	1750H	Lr. Stbk.	1942	1881	1855	1852	Upr. Stbk.
MARATTIACEAE												
Marratia douglasii (Presl)Baker												+
OPHIOGLOSSACEAE												
Ophioglossum pendulum (Presl) Clausen						+	+					+
POLYPODIACEAE												
Pleopeltis thunbergiana Kaulf.			+									
Polypodium pellucidum Kaulf.										+		
PSILOTACEAE												
Psilotum nudum (L.) Beauv.	+				+			+				
PTERIDACEAE												
Cibotium chamissoi Kaulf.												+
C. glaucum (Smith) Hook. et Arn.						+	+					+
Coniogramme pilosa (Brack.) Hieron.												+
Pellaea ternifolia (Cav.) Link												+
Sphenomeris chusana (L.) Copel.								+				
MONOCOTYLEDONAE: CYPERACEAE												
Fimbristylis cymosa R. Br.	+											
Machaerina angustifolia (Gaud.) Koyama				+				+	+	+	+	
Uncinia uncinata (L.) Kukenth.											+	+
GRAMINAE												
Andropogon ?glomeratus (Walt.) BSP. (X)					+							

APPENDIX III (Continued). LIST OF PLANTS FOUND ON SAMPLING SITES

	1840L	Kapoho	1955	1840H	1750L	1750H	Lr. Stbk.	1942	1881	1855	1852	Upr. Stbk.
GRAMINAE (Continued)												
Oplismenus hirtellus (L.) Beauv.		+				+						
LILIACEAE												
Astelia sp.												+
Cordyline fruticosa (L.) Goepp.	+	+										
Smilax sandwicensis Kunth						+						+
ORCHIDACEAE												
Arundina bambusaefolia Lindl. (X)	+		+	+	+							
Spathoglottis plicata Bl. (X)	+		+			+	+					
PALMAE												
Cocos nucifera L.	+											
PANDANACEAE												
Freycinetia arborea Gaud.						+	+					
Pandanus tectorius Park.		+										
DICOYLEDONAE: ANACARDIACEAE												
Schinus terebinthifolius Raddi (X)					+							
APOCYNACEAE												
Alyxia olivaeformis Gaud.						+						
ARALIACEAE												
Cheirodendron trigynum (Gaud.) Heller									+			+

APPENDIX III (Continued). LIST OF PLANTS FOUND ON SAMPLING SITES

	1840L	Kapoho	1955	1840H	1750L	1750H	Lwr. Stbk.	1942	1881	1855	1852	Upr. Stbk.
CASUARINACEAE												
<u>Casuarina equisetifolia</u> L. (X)	+											
COMPOSITAE												
<u>Dubautia scabra</u> (D.C.) Keck								+				
<u>Pluchea odorata</u> (L.) Cass. (X)	+											
<u>Vernonia cinerea</u> (L.) Less (X)	+											
EBENACEAE												
<u>Diospyros ferrea</u> var. <u>pubescens</u> Fosb.						+	+					
EPACRIDACEAE												
<u>Styphelia tameiameiae</u> (Cham. et Schlecht.) F. Muell.	+			+	+				+		+	
ERICACEAE												
<u>Vaccinium calycinum</u> Smith								+	+	+		
<u>V. reticulatum</u> Smith	+			+				+		+	+	
EUPHORBIACEAE												
<u>Aleurites moluccana</u> (L.)Willd.		+										
<u>Antidesma ?platyphyllum</u> Mann						+						
GESNERIACEAE												
<u>Cyrtandra ?platyphylla</u> Gray												+
GOODENIACEAE												
<u>Scaevola taccada</u> (Gaertn.)Roxb.	+											

APPENDIX III (Continued). LIST OF PLANTS FOUND ON SAMPLING SITES

	1840L	Kapoho	1955	1840H	1750L	1750H	Lr. Stbk.	1942	1881	1855	1852	Upr. Stbk.
LOBELIACEAE												
Lobelia sp.												+
LOGANIACEAE												
?*Labordia* sp.												+
MORACEAE												
Cecropia peltata L. (X)							+					
MYRSINACEAE												
Ardisia elliptica Thunb.						+						
Ardisia sp.									+			+
MYRTACEAE												
Metrosideros polymorpha Gaud.	+		+	+	+	+	+	+	+	+	+	+
Psidium cattleianum Sabine				+	+	+						
P. guajava L.		+		+			+					
ONAGRACEAE												
Epilobium ?cinerium A.Rich. (X)								+				
PIPERACEAE												
Peperomia ?cookiana C.DC.												+
Peperomia sp.					+	+						
ROSACEAE												
Osteomeles anthyllidifolia (Sm.) Lindl.					+							
Rubus rosaefolius Sm. (X)						+						

APPENDIX III (Continued). LIST OF PLANTS FOUND ON SAMPLING SITES

	1840L	Kapoho	1955	1840H	1750L	1750H	Lwr. Stbk.	1942	1881	1855	1852	Upr. Stbk.
RUBIACEAE												
Coffea sp.							+					
Coprosma ernodeoides Gray									+		+	
C. menziesii Gray										+	+	+
Coprosma sp.									+			
Gouldia terminalis Hook. et Arn.												+
Hedyotis centranthoides (H.and A.) Steud.								+		+	+	
Morinda citrifolia L.		+										
Psychotria hawaiiensis Gray						+	+					+
URTICACEAE												
Pipturus sp.		+				+					+	
Stereocaulon vulcani	+		+		+			+	+	+	+	
Rhacomitrium lanuginosum	+		+	+	+			+	+			

APPENDIX IV

CORRELATION MATRIX FOR VARIABLES FROM HISTORIC FLOWS
(Variables listed at end of appendix)

1	1	2	3	4	5	6	7	8	9	10	11
1	1.000	0.819	0.308	0.387	0.048	0.544	0.294	0.356	0.394	-0.024	0.539
2		1.000	0.460	0.498	0.133	0.651	0.480	0.503	0.527	0.154	0.547
3			1.000	0.588	-0.270	0.194	0.966	0.448	0.750	0.525	0.020
4				1.000	-0.347	0.220	0.544	0.923	0.974	0.296	0.054
5					1.000	0.035	-0.140	-0.145	-0.356	0.049	0.216
6						1.000	0.235	0.268	0.229	-0.076	0.677
7							1.000	0.503	0.704	0.569	0.147
8								1.000	0.874	0.307	0.235
9									1.000	0.368	0.037
10										1.000	-0.055
11											1.000

APPENDIX IV (Continued)

CORRELATION MATRIX FOR VARIABLES FROM HISTORIC FLOWS

	12	13	14	15	16	17	18	19
1	0.531	-0.250	0.165	0.169	0.412	0.254	0.571	0.357
2	0.584	-0.100	0.129	0.360	0.025	0.306	0.533	0.306
3	0.074	0.455	-0.301	0.101	-0.112	0.030	0.190	-0.013
4	0.077	0.201	-0.049	0.239	-0.076	0.163	0.113	-0.068
5	0.240	-0.159	-0.091	-0.176	-0.008	-0.010	0.172	0.321
6	0.681	-0.305	0.299	0.301	0.095	0.179	0.583	0.408
7	0.208	0.410	-0.379	0.008	-0.122	0.022	0.300	0.161
8	0.262	0.089	-0.121	0.115	-0.081	0.164	0.249	0.173
9	0.067	0.265	-0.102	0.243	-0.087	0.176	0.122	-0.080
10	0.098	0.556	-0.551	-0.236	-0.238	-0.273	0.181	0.187
11	0.957	-0.285	0.044	-0.091	0.205	-0.103	0.911	0.836
12	1.000	-0.183	-0.016	-0.083	0.094	-0.171	0.935	0.862
13		1.000	-0.781	-0.347	-0.502	-0.611	-0.030	-0.031
14			1.000	0.765	0.093	0.594	-0.236	-0.389
15				1.000	-0.374	0.700	-0.335	-0.566
16					1.000	0.126	0.292	0.292
17						1.000	-0.325	-0.420
18							1.000	0.925
19								1.000

Note: Correlation coefficients must be greater than 0.246 (sign ignored) in order to reach the 95% confidence level (65 degrees of freedom).

APPENDIX IV (Continued)

CORRELATION MATRIX FOR VARIABLES FROM HISTORIC FLOWS

List of Variables

1 Δ pH
2 pHc
3 Sodium loss
4 Calcium loss
5 Titanium gain
6 110-350° F. weight loss
7 Sodium loss relative to titanium
8 Calcium loss relative to titanium
9 Combined calcium + sodium loss
10 Depth of organic horizon
11 Timber volume estimate
12 Time (=Age)
13 Mean annual rainfall
14 Rock texture
15 Combined calcium + sodium content of unweathered rock
16 Rock porosity
17 Titanium content of unweathered rock
18 Effective plant factor
19 Mean annual temperature