NEW ZEALAND
DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

NEW ZEALAND GEOLOGICAL SURVEY
(R. W. WILLETT, Director)

BULLETIN n.s. 63

The Geology and Hydrology of Western Samoa

By
D. KEAR and B. L. WOOD
New Zealand Geological Survey

1959

THE GEOLOGY AND HYDROLOGY OF WESTERN SAMOA

Frontispiece: South coast of Upolu Island with weakly columnar pahoehoe basalt in the foreground, Salani lava slopes in middle distance, Fagaloa hills and Mulifanua cinder cone in far distance (centre).

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Petrography by R. N. Brothers

University of Auckland

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Price—40s.

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N.Z. geol. Surv. Bull. n.s. 63.

92 pp., 41 text figs., 5 maps.

R. E. OWEN, GOVERNMENT PRINTER, WELLINGTON, NEW ZEALAND—1959

FOREWORD

The fieldwork that forms the basis of this bulletin developed as an extension of a part of a phosphate search in Australia and New Zealand and their dependent territories, carried out jointly by the Bureau of Mineral Resources, Geology and Geophysics, Canberra, and the New Zealand Geological Survey. Western Samoa was examined by D. Kear and B. L. Wood, officers of the New Zealand Geological Survey, who jointly studied the geology, hydrology, and mineral resources and prepared this bulletin.

After a general introduction the chapters of this bulletin fall into two parts. Chapters 2 to 5 deal with the purely geological aspects of the work, describe the rock formations mapped, the geological structure of the Territory, and contain the evidence from which many of the conclusions and recommendations of Chapters 6 and 7 are derived.

Chapters 6 and 7 present the relevant information and recommendations regarding water supplies. The basic theoretical factors in the general use of underground water are described; the possible sources of water in Samoa are listed and described, the technical, administrative, and educational requirements of Samoan water supply are discussed; the present supply position is reviewed; and the suggested sources of supply are given for most of the Territory. Recommendations are based on published experience elsewhere (notably Tutuila and Hawaii) and may have to be revised in the light of experience in Western Samoa itself.

R. W. WILLETT,

Director, N.Z. Geological Survey.

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CHAPTER 1—GENERAL INFORMATION

Introduction

THE area described in this bulletin comprises the Trust Territory of Western Samoa, and consists of Upolu Island (approximately 430 square miles), Savai'i Island (approximately 730 square miles), and the small adjacent islets of Apolima, Manono, Nu'utele (Vini), Nu'ulua, Namu'a, and Fanuatapu. The Territory lies between 171° 20′ and 172° 50′ W longitude and 14° 10′ and 13° 20′ S latitude, about 525 miles east of Fiji and 1,500 miles north-north-east of New Zealand. It is part of the 300-mile-long Samoan archipelago, the other main islands (in American Samoa) being Tutuila, Ofu, Olosega, Tau, and Rose.

Savai'i and Upolu islands are moderately well roaded, the former with discontinuous coast roads, the latter with coastal and two cross-island roads. All islands are covered with moderately dense tropical forest, which, however, does not render progress as difficult as in many types of New Zealand forest. Upolu Island is narrowly elliptical in outline, roughly 47 miles by 16 miles; a rugged chain of volcanic cones forms the crestal ridge rising to 3,600 ft. Savai'i Island, 47 miles by 27 miles, consists of broad coalescing domes topped by numerous cones, of which the highest rise to over 6,000 ft.

Climate*

The climate is tropical, with two distinct seasons, a wet summer and a drier winter. Temperature ranges, both daily and seasonal, are slight, the mean daily temperature remaining at about 80° F. Although Samoa lies outside the normal track of hurricanes, occasional severe storms are experienced. Over the last 65 years the average maximum temperature at Apia has been 85·0° F, the average yearly rainfall 112·77 in., and the average yearly relative humidity 83·6 per cent, ranging from 80·4 per cent in August to 84·8 per cent in February and March. The average number of hours of bright sunshine per year, based on 31 years' records, is 2,543·9. Average rainfall maps were given by Curry (1955, p. 34).

The climatic conditions largely defeat the restrictions imposed by relatively poor soils; and the steady heat and plentiful rain combine to produce lush growth in forests and plantations.

Population†

The total population of the Territory at the census of October 1956 was 97,327. Since 1900, when the indigenous population was 32,875, the number has almost trebled.

TABLE 1. Climatic Data for Apia, 1951–55

	1951	1952	1953	1954	1955
Total rainfall (inches)	92·38	89·34	76·66	139·75	137·13
Number of rain days	190	200	169	266	247
Maximum daily rainfall (inches)	4·55	4·40	3·04	6·83	5·19
Date	16 Jun	11 Apr	23 Mar	16 Mar	13 Mar
Extreme maximum temperature (°F)	90·2	92·0	91·0	90·4	88·9
Date	17 Apr	31 Jan	20 Mar	6 Feb	14 Apr
Extreme minimum temperature (°F)	64·2	67·4	60·0	66·2	68·2
Date	22 Jul	29 Sep	18 Aug	5 Jul	24 Sep
Mean daily temperature (24-hourly values – °F)	79·69	80·35	80·18	79·78	79·28
Total hours bright sunshine	2,748·0	2,560·9	2,653·0	2,396·1	2,578·4

* Data supplied by Meteorological Office, Apia Observatory, New Zealand Department of Scientific and Industrial Research, and New Zealand Air Department.

† Information supplied by the Census Department, Apia.

The population of the various islands, and the number of villages, is as follows:

TABLE 2. Population, Villages and Sub-villages

Island	Upolu	Savai'i	Manono	Apolima
Population ..	69,206	26,898	1,100	123
Number of Villages (and Sub-villages)	141	112	7	1

The total population is classified in Table 3. The only designations having recognised domestic status are Samoan and European. The table includes a large number of part-Samoans who have adopted either status, a small number of other Polynesians such as Niue Islanders, Solomon Islanders, Tongans, etc., who have Samoan status, and a few non-Polynesians, such as Chinese, who have European status.

TABLE 3. Total Population

Race or Group	Numbers		
	Males	Females	Total
Samoans	44,905	43,131	88,036
Part Samoans ..	4,077	3,823	7,900
Europeans	393	269	662
Other Pacific Islanders ..	321	210	531
Others	137	12	149
Not stated	30	19	49
	49,863	47,464	97,327

Archeological evidence shows that in pre-European times most of the inhabitants were forced to live in the high interior of the island to avoid recurrent raids by sea-faring groups from other islands in the Pacific. The former villages were usually sited at or close to easily defendable strong points and were always within reach of a permanent water supply.

When the situation along the coast became easier, the Samoans of the interior were probably only too happy to leave the cool, wet climate and the poor soils of the uplands for the much pleasanter living conditions of the coast.

The present distribution of population is not in the best interests of the Territory, the villages and developed land being virtually confined to a narrow strip around the coasts. Such strip development is very much influenced by the fact that water supplies are normally limited to coastal springs or shallow wells in coastal alluvium and basalt. Similar strip development was actually observed in the process of formation along the two new cross-island roads in Upolu, where bicycles, hung with water buckets and travelling considerable distances each day to and from distant springs or pipe-systems, afforded new means of obtaining meagre quantities of water for domestic use.

With the rising pressure of increasing population in the coastal strip and the urge to plant more land in bananas and other export crops, there is a growing need to utilise more fully the soils of the foothills, the region between the coastal strip and the high interior. At the present time the population is largely forced to dwell near the coastal water supplies and at a considerable distance from the newly developed plantations.

It seems almost certain that better distribution of the population and more efficient farming of the land will follow if satisfactory water supplies can be developed at various inland points in the vicinity of the good agricultural soils.

Means of Communication

Upolu Island is moderately well roaded, with a road, mostly tar-sealed, along the northern and western coasts, and two cross-island roads, one of which links with the south coast road, and the other with the east coast road that continues to Ti'avea village on the north-east coast.

Savai'i Island has two long stretches of mainly coastal road, and a few short inland roads to villages and mission stations. It is proposed to connect the main stretches between Sili and Salailua.

Transport is provided in both islands by locally owned bus services, and between the islands by small copra boats and ferry launches plying on regular schedules.

In addition to the normal postal and telegraphic facilities, a system of Government-owned radio receivers in the villages enables news and messages to be communicated from the local radio station to even the most remote districts.

Industries

Industries are few in number and are devoted mainly to agricultural products. By far the greatest number of people are plantation labourers or owners. The chief exports are copra (17,178 tons in 1955), cocoa (3,041 tons), and bananas (445,870 cases), with only small quantities of rubber, hardwoods, and curios. Small local industries include coffee processing, timber milling, and cattle raising (for meat, milk, and hides). Only small quantities of local produce are sold for cash. The tourist trade has not been an important industry to date.

Soils

The soils of Western Samoa were briefly described by Hamilton and Grange (1938), and have been recently mapped in detail by Mr A. C. S. Wright, New Zealand Soil Bureau, who supplied some of the following comments. They are predominantly stony latosolic soils of varying fertility, containing unusually high amounts of titanium oxide (7·8 to 12·6 per cent).

Despite the high rainfall, soil erosion is practically absent, as conditions prevent much run-off of rainwater. Most soils have a good structure and subsoils are not compact. According to Hamilton and Grange (1938, p. 602) the factor most likely to affect agriculture on these soils is deficiency of potash and/or phosphate.

Soils derived from scoria are nearly always deeper than those derived from lava but amongst the latter there is very good correlation between depth of soil and the age of pahoehoe lavas. The historic volcanic flows on Savai'i have scarcely begun to form soil, and the depth of soil increases progressively over the Puapua, Mulifanua, and Salani pahoehoe lavas. The deepest sedentary soils in Western Samoa are found over the Fagaloa Volcanics.

Fieldwork and Maps

The fieldwork, in which the authors were assisted by Mr S. Poutoa, lasted from 15 August to 29 October 1956. Mr Poutoa, normally attached to Public Works Department, Apia, acted as interpreter, field assistant (especially on hydrological work), and draughtsman. During this time, full use was made of the facilities of the Lands and Survey Department, and of Mr A. C. S. Wright's organisation for a soil survey. From time to time the facilities of the Public Works, Agriculture, Air, and Fire Departments were also used. The geological party, and the soil survey party under Mr A. C. S. Wright, were frequently together in the field, to the mutual benefit of both.

Maps were prepared using air photographs made in 1954 by New Zealand Aerial Mapping Ltd. for the New Zealand Department of Lands and Survey. The geological boundaries of Upolu Island, and other information, were plotted on maps traced from air-photograph mosaics, which were subsequently reduced to a single map on a scale of 1 : 100,000. For Savai'i, the information was plotted on air photographs (about 30 chains to an inch), and reduced and corrected to conform to a base map prepared by the Western Samoan Lands and Survey Department. The mosaic tracings of Upolu were reduced, and the final maps were draughted by the Draughting Section, New Zealand Geological Survey.

Acknowledgments

The geological party was greatly assisted by Mr A. C. S. Wright, especially in the early stages of the work, through his familiarity with local conditions, and the work in Upolu was facilitated by his prior soil survey. The use of Mr Wright's soil maps in compiling parts of the geological map of Upolu is gratefully acknowledged, as are many fruitful discussions with him.

The geological party was afforded transport and office and draughting facilities by the Western Samoan Lands and Survey Department, and much advice and assistance was given by the Chief Surveyor, Mr I. F. Stirling. Grateful acknowledgment is made to the Lands and Survey Department of Western Samoa for permission to publish figures 1A and 1B, 2, 4, 10, 11, 12, 13, 14, 17, 18, 19, 27, 29, and 31.

Officers of the Public Works Department also cooperated, especially in details of present and proposed water and power schemes, and in the supply of equipment for deep-well measurements and for transport.

Numerous hosts in both islands provided accommodation, and arranged for the employment of local guides, porters, and boatmen.

In this bulletin the several sections on the petrography of the various formations are solely the work of Dr R. N. Brothers of Auckland University, who studied thin sections of rock specimens collected by the authors (see list in Appendix). The authors' thanks are also due to Dr Brothers for reading the manuscript and making helpful suggestions on petrological topics.

Mr I. F. Stirling has contributed a section on Gravity Anomalies, which the authors gratefully acknowledge.

Previous Work

The first geological descriptions of Samoa were by Dana (1849, p. 307–36), who spent only a few hours on Tutuila, and longer on Upolu. He visited the craters of Tafua upolu and Lanuto'o, and observed dips of 3° to 6° in the lavas. He recorded recent lavas near Apia, Lauli'i, and on the opposite coast south of Apia, and noted that Nu'utele (Vini) and Nu'ulua Islets, and Cape Tapaga nearby, were tuff cones containing embedded coral fragments. He recognised the main fissure system of Upolu parallel to the axis of the island, and indicated the youthful appearance of the western district as contrasted with the greater age of the central and north-eastern parts that resembled Tutuila and Manua. Savai'i Island was stated to be a large single basaltic volcano like Mauna Kea in Hawaii. He considered that the Samoan Islands were built over two separate fissures, that the oldest eruptions in Upolu were comparable in age to those of Tahiti and Kauai, and that the youngest post-dated the present coral reef.

A number of rock specimens from Upolu and a few from Savai'i were described petrographically by Möhle (1902, p. 93–104): olivine basalt predominated, three limburgites were noted, and palagonite tuff was recorded from Apolima and Fanuatapu Islands.

A specimen of the 1902 lava, from Mauga Afi, Savai'i, was examined by Kaiser (1904, p. 121). The Matavanu lava flow of 1905 was described by Klautsch (1907, p. 174) who presented a chemical analysis of the rock by Heuseler. The historic eruptions in Savai'i and the 1905 flow were described by Jensen (1907), and petrological descriptions were given of four other specimens of olivine basalt from Savai'i (one containing enstatite), and three from Upolu. Jensen considered (p. 646) that the coral sand and swamps fringing the coast from Pu'apu'a southward indicate a recent uplift amounting at the most to 6 or 8 ft. An analysis of the Matavanu lava given by Jensen (1908, p. 706–7) differs somewhat from that given by Heuseler.

Later stages of the Matavanu eruption are described by Angenheister (1909), Anderson (1910, 11, 12), Friedlander (1910), and Grevel (1911). Other descriptions, in German publications not accessible to the writers, are those by von Bulow (1906), Friederici (1910), Reinecke (1905, 1906), Sapper (1906, 1909, 1911a, 1911b, 1912, 1915), and Schmittmann (1911). Accounts of the 1902 eruption in Savai'i are given by Wegener (1902, 1903a and b) but are in German publications not accessible to the writers.

Friedlander (1910) explored the interior of Savai'i and described rift zones marked by lines of cones. He also noted the tuff cone of Apolima Island, contrasting with the lava cone of nearby Manono Island, and suggested that the estuaries of Upolu Island indicated recent submergence. His collection of rocks was examined and described by Weber (1909), whose work was reviewed by MacDonald (1944).

Park (1914, p. 228) briefly mentioned the existence of pillow structures in the lavas from Matavanu crater where the rocks meet the sea. Although Jensen (1907, p. 652) described similar features in process of formation, no true pillow forms were seen during the present work.

Thomson (1921), following a six-week visit to Samoa, described the main features of the geology and presented a small map showing the historical eruptions in Savai'i. He reviewed the geological literature extensively, and presented observations previously recorded only in German administrative reports. He summarised the historical eruptions of Savai'i and visited the volcano of Matavanu, where sulphur fumaroles were still active. He considered that the high cliffs of the south and east coasts of Upolu were due to faulting, and not to drowning of a steep terrain. The strip of coral sand bordering the coasts was thought to be aeolian in origin (following Friedlander) rather than a raised beach deposit.

Daly's description of the geology of American Samoa (1924) contained many references, by way of comparison, to Western Samoa.

Bartrum (1927) described petrologically the specimens collected by Thomson and by F. Woods, a member of the New Zealand Geological Survey on military duties in Samoa. Most were olivine basalts, one contained hypersthene, and a few were picritic basalts. Four chemical analyses by F. T. Seelye were presented, including two of picritic basalts and one of an orthoclase trachyte.

Bryan (1941, p. 101) presented the dates of the historical eruptions, and reported that the Matavanu crater was emitting steam during his visit in 1924. He compared the tuff crater of Apolima Island to that of Nu'utele (Vini), and mentioned that on Manono Island the coastal springs are brackish and the villagers depend on rainwater.

A detailed description of the geology of American Samoa by Stearns (1944) includes a short section on Western Samoa, and the petrology is described by MacDonald (1944).

Stearns subdivided the volcanics of Upolu into three age groups based mainly on weathering and erosion: Pliocene or earliest Pleistocene, middle and late Pleistocene, and Recent. A geological sketch map of Upolu showing these subdivisions includes generalised bathymetrical information. The oldest division, corresponding to the Fagaloa Volcanics of the present work, was recognised in both Savai'i and Upolu Islands; rocks of the middle division were found to be most plentiful in both islands, and were erupted from chains of craters and cones aligned along rift zones trending generally at 110°. The youngest division included the reef-covering lavas of Savai'i, and small valley-filling flows in Upolu.

Stearns recorded the absence of a living barrier reef along coasts formed of Pliocene rocks; this is contrary to the usual assumption that reefs surround old rather than young rocks in the coral seas. The formation of barrier reefs off coasts of Pleistocene lavas was shown to be a consequence of the gentle slopes of the lavas, coupled with a rapid rise of sea level. The barrier reefs, 120 ft thick and 2 miles wide, were considered to have been built since late Pleistocene time, and probably resulted from upward growth of a fringing reef formed during low sea level. Remnants of the eustatic 5 ft stand of the sea were noted.

The geological histories of the various islands of the Samoan archipelago were found to be remarkably similar, and were summarised by Stearns (1944, p. 1330–1):

> Pliocene or earliest Pleistocene – rapid extrusion of olivine basalts, cone and caldera formation, caldera filling, appearance of more differentiated rocks, and waning of eruptions with appearance of trachytic lavas.
>
> Early and middle Pleistocene – a period of stream and marine erosion, canyon formation, and coral-reef growth, submergence of at least 400 ft, growth of wide barrier reefs and, finally, fresh volcanism on Savai'i and Upolu.
>
> Late Pleistocene – continued volcanic activity on Savai'i and Upolu, burying of coral reefs, submergence of about 200 ft (possibly due to melting of polar ice of the Last Glaciation), simultaneous growth of barrier reefs on gently shelving coasts and, finally, emergence of 20 ft.
>
> Recent – continued volcanism forming offshore tuff cones and lava flows (some filling valleys), growth of fringing reefs, and a late emergence of 5 ft.
>
> Historic – continued volcanism on land with a submarine eruption in American Samoa in 1866.

The petrography of the Samoan Islands, particularly of Tutuila and Upolu, was described by MacDonald (1944), who examined the specimens collected by Stearns and summarised the previous work. Thirty specimens from Upolu and two from Savai'i are described. The oldest lavas of Upolu were found to be predominantly olivine basalts, and less commonly olivine-poor basalt, picritic basalt, basaltic andesite, and in one case trachyte. Almost all the Pleistocene and Recent lavas of Upolu, and the young lavas of Savai'i, were identified as olivine basalts. MacDonald presented all available chemical analyses of Samoan rocks, indicated that the suite is alkalic with an alkali-lime index of 50·5, and concluded that differentiation probably occurred by crystal settling.

Curry (1955) in discussing the physical geography, climate, soils, vegetation, and surface waters of Western Samoa, stated that the slope on younger lavas (Mulifanua and Salani in this report) rarely exceeds 9°, reported that the only permanent streams flow on the more weathered rocks, and drew attention to the absence of reefs opposite recent lavas and steep coasts. Diagrams show slope, rainfall, geology, and surface water supplies. His small sketch map of the surface rocks included the following subdivision: Slag and Cinder Cones, Very Recent Lava Flows, Recent Lava Flows, Eroded Weathered Basalts, and Young Basalts. Curry stated that soils on the recent flows are very fertile but sparse, young basalt soils are thick and fertile, and higher soils are deeper and more acidic.

CHAPTER 2—PHYSIOGRAPHY

Outline of Geology

The predominantly basaltic rocks of the Territory have been erupted from a great number of volcanic cones distributed over the uplands. The oldest rocks occur mainly on Upolu Island, and the youngest on Savai'i, but clearly volcanism has been contemporaneous in both throughout much of upper Quaternary time. The geology is summarised in an "Index Map" (fig. 40) presented at the end of the index.

The general structure is that of a deeply eroded Pliocene or early Pleistocene volcanic terrain, flanked and largely buried by late Pleistocene and Recent lavas. The rocks are divisible into six formations, and these, together with a series of marine tuffs, and three sedimentary formations, are shown in order in Table 4, together with some of the criteria on which correlations and relative ages are based.

The oldest rocks, the Fagaloa Volcanics, occur most plentifully in the north-eastern district and the central mountains of Upolu, to a lesser extent in south-western Upolu, in a small area of northern Savai'i near Fagamalo, and in the bottom of deep gorges in south central Savai'i. They consist of basaltic lava flows of aa and pahoehoe in regular sequence, either non-porphyritic or containing phenocrysts of olivine, augite, and feldspar, with associated dykes, tuffs, and cone deposits. They characteristically form steep-sided high mountains with slopes of 25° to 50°, and rise, monadnock-like, above the gentler slopes of the later lavas. Only inland from Lauli'i, a few miles east of Apia in Upolu, are the original surface slopes of Fagaloa lavas preserved, and there they (and the underlying flows) dip northwards from the axis of the island at from 5° to 20°.

The distribution of the Fagaloa rocks, and the few dips observed, indicate that the rift zone through which those lavas rose was approximately parallel to, and probably identical with, that of the younger lavas.

The Vini Tuff, either post-Fagaloa and pre-Salani or intra-Salani in age, entirely constitutes the outlying islands (with the exception of Manono) and occurs at Cape Tapaga, south-eastern Upolu. It forms dissected and partly dismembered tuff cones, consists mainly of vitric-lithic tuff, and contains scattered mollusc shells up to 30 ft above sea level and small rare coral fragments up to about 400 ft.

Rocks of the four most widely distributed volcanic groups, (Salani, Mulifanua, Lefaga, and Puapua) rest unconformably on, and fill valleys eroded in, the Fagaloa rocks. They strongly resemble one another petrologically, being mainly olivine basalts, but, as shown in Table 4, they differ in other features. The most important features are: for the Salani, the deep soil and weathering and the evidence of a pre-Mulifanua canyon-cutting episode; for the Mulifanua, the existence offshore of the widest barrier reefs and the presence of only shallow stream channels (alias); for the Lefaga, lack of dissection and the presence of only a narrow fringing reef offshore; and for the Puapua, the thinness of the soil, and the way in which the lavas flowed over the wide reefs to form rocky iron-bound coasts. The composition, the ubiquitous aa-pahoehoe structures, and the broad dome forms of these volcanics all suggest that they are primitive basalts associated with an entirely new cycle of volcanism, not following on that of the older Fagaloa activity.

The Aopo Volcanics and their associated cones were all erupted within the last 200 years, the latest eruption ceasing in 1911. They occur only in northern Savai'i. The lavas are predominantly fresh porphyritic pahoehoe, with aa common only near the cones. They fill valleys in older rocks, probably to depths of over 1,000 ft (Jensen, 1907, p. 650), have flooded out to and spilled over the iron-bound Puapua coasts (see p. 45), covered portions of a barrier reef and, flowing lengthwise along the coast, filled the lagoon.

Cones occur plentifully on the uplands of Upolu and Savai'i, in chains or groups having a prominent 110° alignment. The ages of the cones range from Salani to Aopo, and are indicated by the greater degree of weathering, and amount of dissection and decay of the older ones. They consist of various mixtures of grey, red, or black scoria, cinders, tuff, basaltic breccia, spatter, lapilli, rarely bombs, and thin flows of basalt.

2

TABLE 4. Western Samoan Rock Formations

Name	Cover of Vegetation	Weathering Zone and Soil	Present Reef	Boulders on Uneven Land	Alterations to Cone Form	Surface Water	Olivine Nodules	Age
Aopo Volcanics ..	None or poor	None	None	Very common	None	None	Rare	Historical
Tafagamanu Sand ..	Sedimentary formations approximately contemporaneous with Puapua Volcanics							Post-Glacial + 5 ft sea level
Nu'utele Sand ..								Post-Glacial + 15 ft sea level
Lalomauga High-level Alluvium								Post-Mulifanua
Puapua Volcanics ..	Normal	Very thin	None	Very common	None	Virtually none	Rare	Middle to late Holocene
Lefaga Volcanics ..	Normal	Intermediate	Close inshore	Very common	Little	Virtually none	Rare	Early Holocene
Mulifanua Volcanics	Normal	Intermediate	Far offshore	Common, weathered, angular	Crater filling	Rare	Uncommon	Last Glaciation
Erosional unconformity, with canyon formation								
Salani Volcanics ..	Normal	Thick (over 12″ soil)	Far offshore	Very weathered rounded	Gorges cut in flanks	Sometimes	Present	? Penultimate Glaciation or Last Interglacial, to early Last Glaciation
Vini Tuff	Marine tuff rings, definitely pre-Lefaga, post-Fagaloa, and probably early Salani							Last Interglacial (about + 30 ft sea level)
Great erosional unconformity, beneath younger volcanics								
Fagaloa Volcanics ..	Can be poor (leaching)	Very thick	None or close inshore	Rare	Up to complete destruction, dykes exposed	Always	Common	Pre-Penultimate Glaciation – possibly late Pliocene

Littoral cones, of which there are very few, the most notable being Tafua savai'i, consist mainly of brown vitric tuff, a product of the interaction of the hot magma and ground water. Small adventitious cones, or ash rings, occur at a few places, e.g., Mauga (see fig. 19, A), where sea water, trapped below hot Aopo lava that filled the lagoon, exploded through as steam.

Sedimentary rocks are sparse and occur mainly at low altitudes. They include Lalomauga Alluvium laid down when tributary valleys were blocked by a lava flow down the main Falefa Valley, Nu'utele Sand deposited by the sea when 15 ft above the present level, Tafagamanu Sand, 5–6 ft above sea level, undifferentiated thin sheet-flood and river-mouth gravels, swamp muds, coral reefs, and cemented beach sands at present sea level.

Cones and Cone Forms

Upolu and Savai'i are much the largest and most mountainous islands of the Samoan Archipelago. The volcanic cones of Upolu have a well marked alignment and form a distinct crest; those in Savai'i are distributed in chains over a very broad convex plain on the summit of the rather dome-shaped island (fig. 1A, 1B).

The largest cones occur between altitudes of 2,000 ft and 3,000 ft in Upolu, and up to 6,000 ft in Savai'i. The larger craters are between a quarter and half a mile in diameter (fig. 2). Smaller cones, up to 800 ft in height, may be located well away from the crests of the islands and are of only subsidiary importance. Typical cone profiles are shown in fig. 3 (from Stearns and MacDonald, 1946, fig. 5).

Two extreme cone types can be recognised in Samoa with every gradation between them. Lava cones (e.g., Manono Island) are those that have given rise to one or more major lava streams and have thrown out relative small quantities of cinders and scoria. The cone slopes approximate to the gradients of the lava flows and present a low concave profile (fig. 3).

Scoria and cinder cones are much more common and are generally smaller and single. Their slopes are steeper, up to 40°, and correspond approximately to the angle of rest of the ejected material. The older Salani and Mulifanua cones may have reddish slaggy or scoriaceous blocks (bombs)

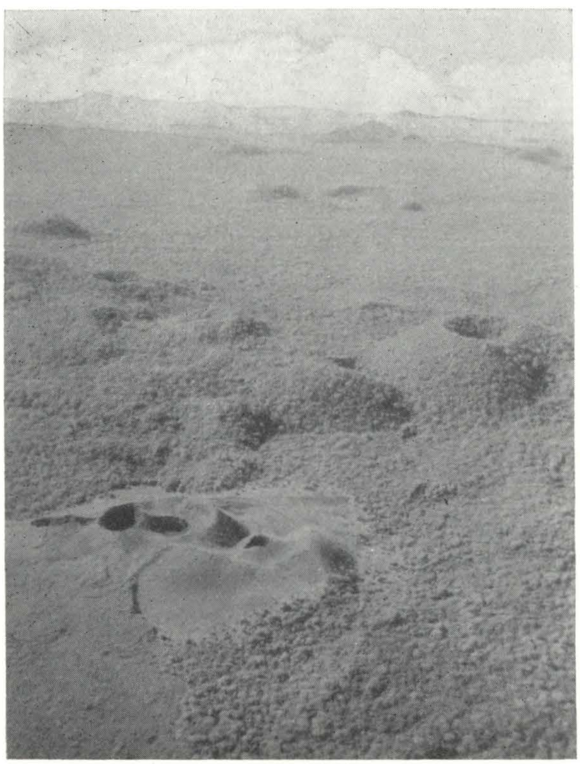

Fig. 1A: View south-east, from the air, of the central uplands of Savai'i Island, (5,000 ft), showing the broad convex lava plain and numerous cinder cones. The bare cone in the foreground is Mauga Mu (5,260 ft), which erupted in 1902.

Fig. 1B: Vertical view of same area as in fig. 1A. Maugu Mu, 5,260 ft (right), and unnamed cones (left) lie on a fault scarp. The short lava flows spilled over two other fault scarps, shown by light reflected from steeper slopes and by constriction on flows. The upper scarp is some 500 ft high and extends for 10 miles from Sataua.

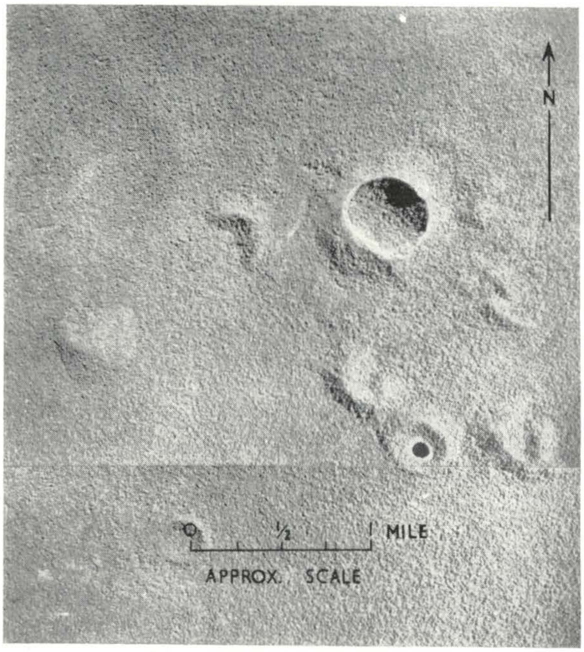

Fig. 2: Vertical aerial view of Savai'i uplands inland from Tapu'ele'ele showing cones of To'iavea (3,477 ft) and Mataulano, and crater lake in latter.

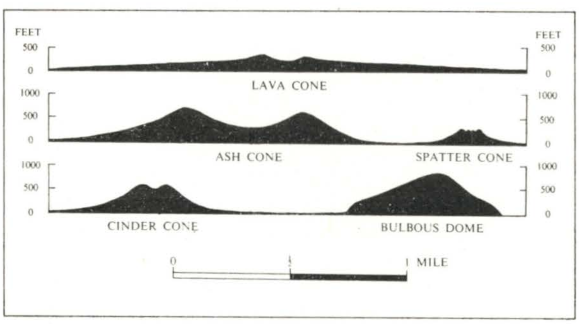

Fig. 3: Typical cone profiles (Stearns and MacDonald, 1946, fig. 5).

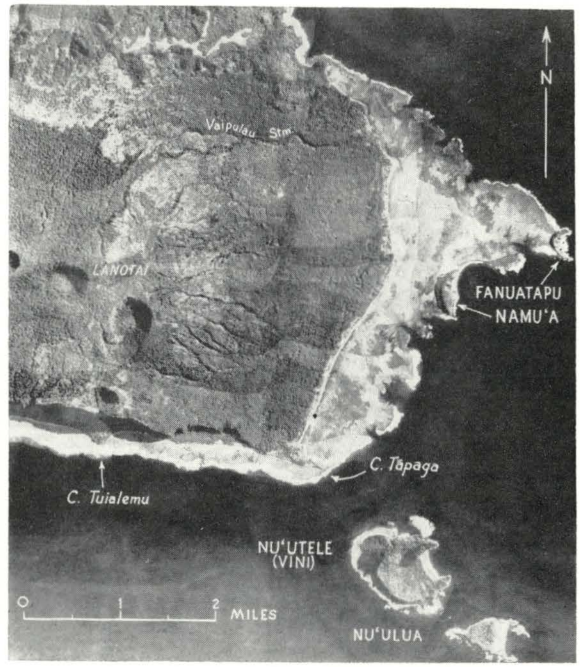

Fig. 4: Aerial view of south-east Upolu and outlying islands of Vini Tuff. Salani lava slopes and cones on land with rudimentary valley development; dissected hills with bare tops of Fagaloa Volcanics at the top of the illustration. The coral reef off the eastern Salani coast is very much wider than that off the southern, cliffed, fault coast.

scattered about their surface and throughout a reddish slippery clay soil (e.g., Salani cones on the Tapu'ele'ele track); or may have a clinkery slaggy cover over a brown soil of weathered ash (Falealupo road). Younger large cones (To'iavea, Mataulano) commonly have very rough, slaggy slopes. In contrast, some young cones (Mauga Silisili) are veneered with brittle black cinders and blocky cinder superficially resembling aa lava. The cones of Mauga Mu, Savai'i (fig. 1), erupted in 1902, consist of fine black glassy cinder so incoherent and dry that one sinks ankle-deep in it. Similar material covers many acres of the surrounding highland. A few cones enclose crater lakes, such as Lanuto'o in Upolu, and Mataulano in Savai'i, but more commonly the craters are flat-floored with swamp underlain by red slippery clay.

Tuff cones are represented mainly by the islands consisting of Vini Tuff (fig. 4). These are much dissected tuff rings or segments of rings, of probably Last Interglacial age. An exception is Tafua savai'i which, although very similar in composition, is much younger and still retains much of its original form.

Lava Slopes

For the most part the lava flows slope at moderate angles (generally up to 10°, but rarely up to 15°) in the uplands, and lend a deceptively low appearance to skylines (fig. 5).

In eastern and north-central Upolu, hills of Fagaloa rocks are very steep, up to 60°, with sharp, narrow crests, and are separated by deep narrow valleys (fig. 6). They have been eroded from an earlier Pleistocene landscape, and are similar in form to other high Pacific islands consisting of older volcanics, e.g., Tutuila, Rarotonga, and Tahiti. Only very small sectors of the old lava surfaces remain, particularly towards the coast near Lauli'i. These slope at some 10° seaward, and have a deep infertile soil on which grow only grasses and xerophytic ferns (cf. the "bare tops" in fig. 4).

In contrast to the convex upper lava slopes, the lower slopes around the coasts have very low gradients, and on the Mulifanua Volcanics a fairly sharp change is discernable at a concavity in the profiles between the higher and lower slopes. The reason for this is evident in the Aopo lavas of Savai'i where flows have covered pre-existing slopes at moderate gradients, and have spread almost horizontally on to a wide coral reef (fig. 5). Mulifanua lavas show this feature particularly well in the Fa'asaleleaga district of eastern Savai'i, and in the western districts of Upolu.

Many, if not all, of the Mulifanua lavas at the lower altitudes have probably buried earlier wave-cut benches and coral reefs. The only positive evidence of a buried reef is in the reported occurrence of coral towards the bottom of Afia well, Mulifanua district, close to present sea level and beneath about 100 ft of Mulifanua Volcanics.

By way of contrast, slopes of Salani Volcanics have no such variations, and continue from the upper convexities, at constant gradients down to the coast. The observer receives the impressions that the slopes are broad because of the great volume of lava poured out, that the slopes probably continue for some depth below sea level (fig. 7), and that any earlier surface, such as a wave-cut platform or a reef, must have been deeply buried.

Both Puapua and Aopo lava slopes have similar gradients to those of the Mulifanua Volcanics, and flatten out where they have covered parts of the post-Mulifanua coral reef. The apron of Puapua lava that has covered the coral reef in the Falealupo area has partly buried a 100 ft cliff cut in Mulifanua Volcanics a mile west of Papa.

Younger lavas have formed cascades and fans over escarpments of older rocks in both islands. This is evident in Upolu in the heads of a few rivers

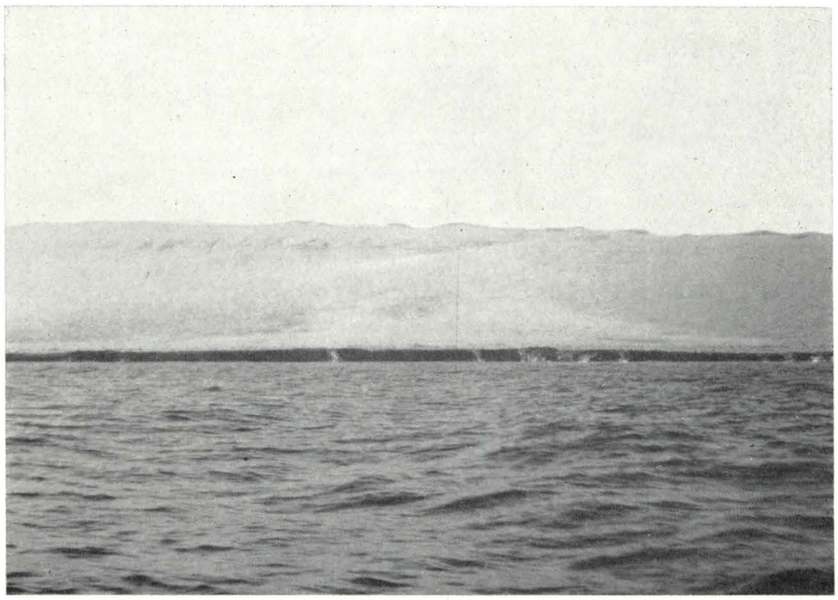

Fig. 5: Coast and uplands of Savai'i from off the iron-bound A'opo coast. The great fan of Aopo lavas spreads from the right-hand skyline and crosses the 500 ft fault scarp visible in the centre distance just below the skyline. The summit cones reach altitudes of 6,000 ft.

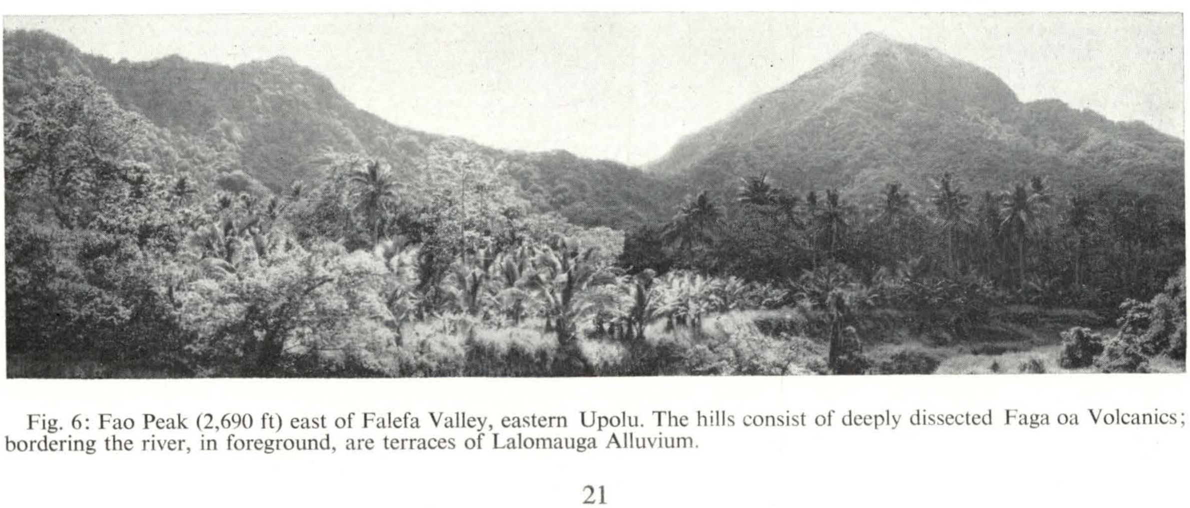

Fig. 6: Fao Peak (2,690 ft) east of Falefa Valley, eastern Upolu. The hills consist of deeply dissected Faga oa Volcanics; bordering the river, in foreground, are terraces of Lalomauga Alluvium.

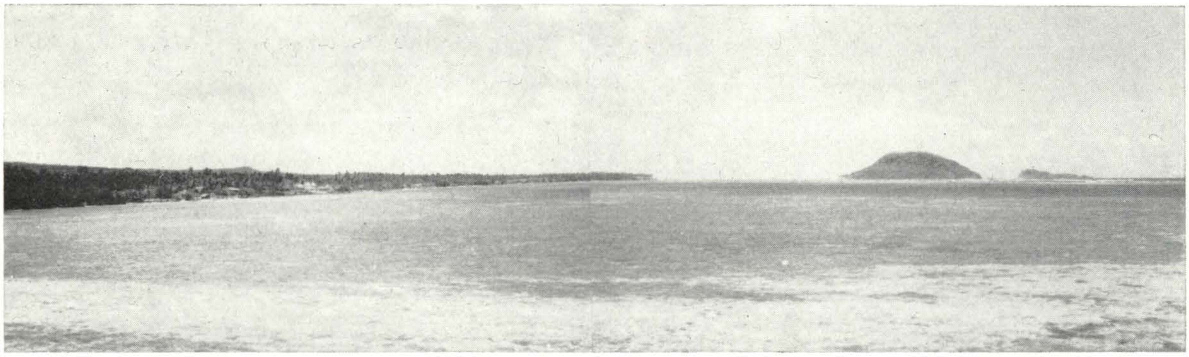

Fig. 7: Eastern coast of Upolu Island from Cape Tapaga. Fanuatapu and Namu'a islands on right, Salani Volcanics on eft. A narrow strip of alluvium borders the coast.

north of the crest of Fagaloa hills (particularly the Falefa and Soaga Rivers) where Mulifanua lavas have overtopped the crest. The Aopo lavas inland of A'opo village have built up a vast broad fan that obliterates a 500 ft scarp along the north side of the crest (fig. 5), while on the south coast near Fagafau village a narrow flow of Puapua lava has spilled over the 200 ft cliffs to form a steep blocky cascade of aa. Another Puapua flow, a mile to the northwest, has cascaded over lower cliffs and covered a strip of Tafagamanu Sand.

Lava Tunnels

Lava tunnels are characteristic of basaltic eruptions, and are fairly common in Samoa. Several have been recorded from the Matavanu lava field near the road; Thomson (1921, p. 61) described one at Falemauga (recorded as being at 1,300 ft, 10 miles south of Apia, in Upolu) that was formerly occupied by Samoans probably during local wars; and another at Paia, Savai'i, described by von Bulow (1906) appears to have been similarly occupied. Others are well known at Tafua savai'i and on Manono Island. Friedlander (1910, p. 519) mentions that there are two tunnels, one above the other, at Tapu'ele'ele, Savai'i. During the present work these were visited and found to be parts of one long tunnel, the middle portion of which had collapsed, so that one tunnel lay upslope of the other, not on top of the other as suggested by Friedlander's report. Just below Tapu'ele'ele village a third portion of the same tunnel was followed for a short distance. The overall length of the three observed portions of this tunnel is some 2,000 yards, and the total length beyond the portions observed is probably very much greater.

Lava tunnels develop during the growth of a lava field and were originally the conduits through which much of the lavas flowed. During the later stages of the Matavanu eruption by far the greatest volume of lava reached the sea by this means, and disappeared over the edge of the overwhelmed coral reef. When the supply of lava to such conduits is cut off or diverted, that in the tunnel drains out leaving only a little in the bottom, so that a cooled tunnel has an almost circular cross section except for a flat bottom.

The height and width of the tunnels is usually constant for many yards, but in places large stalactites and curiously shaped "drooping" masses protrude into the tunnel. The former are caused by refusion of the lava walls by the burning of inflammable gases discharging from the lava stream, the latter appear to be the fused edges of infalling blocks, probably associated with collapsing tumuli or pressure domes above the tunnel.

The tunnels at Tapu'ele'ele (525 ft above sea level) are in Salani basalts and on account of their age have lost much of their original form by surface and wall collapse. At times they carry strongly flowing streams that have considerably trenched the floor and deposited much bouldery alluvium. The tunnels above the village reveal a section in the stream-trenched floor in which the youngest Salani basalts can be seen resting on a thin red crumbly soil layer on the underlying Salani basalt. A cross section of the rocks in the walls and floor is illustrated in fig. 8.

Streams in lava tunnels are obviously just as ephemeral as surface streams on similar basalts, and are no more dependable for water-supply purposes. To judge from the thick deposits of organic waste found in older tunnels, such streams are rare in any case.

The fine organic soily waste is common in older tunnels, many of which are inhabited by a small native bat and a native swift. It is a light earthy friable substance, consisting mainly of chitinous insect remains. The light texture appears to be due to the ceaseless working-over by ants and other insects.

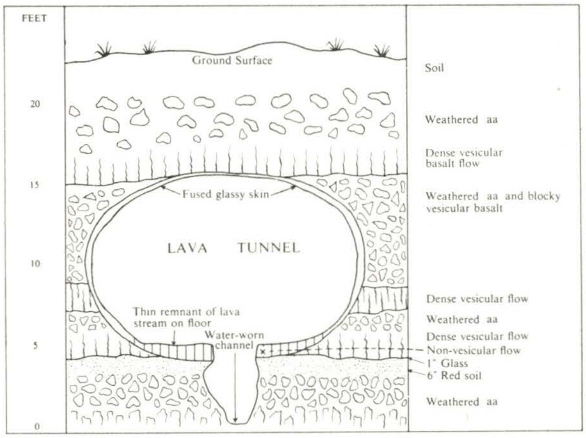

Fig. 8: Cross-section of lava tunnel and wall rocks, Tapu'ele'ele, Savai'i.

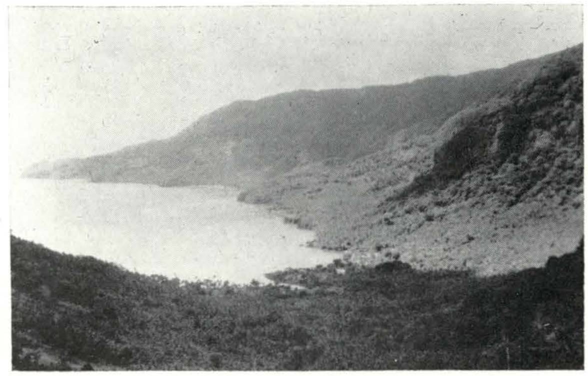

Fig. 9: Fagaloa Bay from Fagaloa Saddle at head of valley. The bay has every appearance of a drowned valley, submarine slopes are probably steep, and only small fringing reefs are present.

Streams and Stream Patterns

General

Stream erosion is a measure of the age of the rocks of a volcanic island, and a wide range of stream-eroded forms is found in Samoa corresponding to the various ages of the rocks. These may be summarised as: youthful graded valleys on Fagaloa rocks; amphitheatre-headed canyons, and deep, poorly graded gully systems on Salani; completely ungraded alias (dry water courses) on Mulifanua and Legafa; and few, short, weakly eroded gutters on Puapua, these usually arising at small springs where the lava cover is thin on older rocks (e.g., Siga Spring in south-east Savai'i).

The streams on Fagaloa rocks are all perennial, being fed during dry seasons from numerous high-level springs. The stream pattern is dendritic and where not modified by younger lavas is undoubtedly controlled to some extent by the geological structure. The pattern, and most large stream valleys, are pre-Salani in age. The main divide of the Fagaloa terrain was close to and immediately north of the divide built up by the later volcanics, and the large Fagaloa and Falefa valleys appear to be inherited from the initial radial drainage pattern on a Fagaloa volcano, the main centre of which was probably close to the present crest of Upolu Island.

The presence of only a narrow fringing reef, the steepness of the coasts and the adjoining land, and the steep submarine slopes nearby all indicate that the Fagaloa terrain has been drowned, possibly several times during the Pleistocene. Fagaloa Bay is a typical drowned valley (fig. 9); Falefa Valley and several of the valleys along the north coast of Upolu were also once drowned, but have later been filled with younger lavas.

The few perennial streams on Salani rocks are still in early stages of youth and have produced three varieties of landform: widely spaced, deeply entrenched gulches with several falls (e.g., Fagataloa or Salani River, fig. 10); complex multiple-gully systems (fig. 11 and 12); and deep amphitheatre-headed canyons (south Upolu, and Savai'i, fig. 13 and 14).

These appear to be related more to the rock structure than to any great differences in ages. The deepest gulches occur on broad low-dipping lava sheets presumably where the Salani Volcanics are thickest, or on a smaller, finer scale, on lava cones (fig. 10); the canyons have most probably developed where ridges of Fagaloa rocks underlie the Salani at shallow depth; and the multiple-gully systems occur on much weathered aa-rich Salani basalts.

Stream Gulches

Gulches are best developed along the Fagataloa River (fig. 10). In its lower reaches the river flows quietly between low rock banks, and it is possible to canoe upstream for almost a mile from the mouth. As the surrounding land increases in altitude, the rock walls become progressively higher upstream, and at the Sopoaga Falls, about 3 miles from the mouth, reach some 200 ft in height. In the walls of the fall basin, thick irregular beds of aa and scoria separate an upper 20 ft lava bed from a lower one that is 80 ft thick. All beds dip 3° to 5° south-east.

Five miles upstream from the mouth, the Fagataloa branches in a gulch some 150 ft deep and 50–160 ft wide, the west branch being the A'uga, with falls some 1½ miles upstream, and the east branch the Vaigafa. The Fuipisia Falls (185 ft high) are located a short distance up the latter, and

Fig. 10: Part of south-eastern Upolu, with Fagataloa River in deep gulch (left) entrenched in Salani Volcanics. The sharp ridge at the top right is the divide of partly buried Fagaloa rocks against which Salani lava slopes have impounded shallow swampy basins (Sw). The cones are Salani and Mulifanua and lie on the main crest of the island. Note the system of gullies on the Salani slopes, the radial pattern on the lava cone in centre, and the young flow (Lefaga) that covers part of lagoon immediately west of Lotofaga village.

about 5½ miles further upstream are the Afulilo Falls (170 ft high). The reaches between the Fuipisia and Afulilo Falls and above the Afulilo are not entrenched: in the lower reach the stable stream gradient is parallel to the low dip of the Salani lava flows that were dammed up between the main axis of eruption and the Fagaloa hills to the north; in the upper reach above the Afulilo Falls the stream meanders across swampy basins.

Between the well developed gulches of the Fagataloa River and the irregularly graded alias described below is every gradation of stream channel and pattern, either radial and consequent on initial lava slopes, or converging towards the junctions of lava slopes.

Canyons

Several large canyons have been cut in Salani Volcanics, both in the Falealili district of Upolu, and in north and south-central Savai'i (fig. 13 and 14). Those in Upolu are as much as 600 ft deep, and those in Savai'i more than 1,000 ft. They have steep amphitheatre-shaped headwalls, over which younger lava flows have cascaded (fig. 13). Some are floored with and partly filled by Mulifanua and younger basalts, others have a veneer of alluvium on Fagaloa rocks, and all were formed at some time between the Salani and Mulifanua eruptions. Those of the Vanu River, south central Savai'i (fig. 14), have a veneer of bouldery alluvium resting on the lava fill.

Although Fagaloa rocks are commonly exposed in the lower walls of the canyons they may not be present, so high above sea level, beneath the country between the canyons. Figure 15 illustrates the probable effects of inversion of relief caused by the extrusion of the Salani Volcanics, and the inferred relationship between the canyons and buried ridges of Fagaloa rocks in the Falealili district, Upolu. The flat floor of the canyons cannot be explained by anything other than structural control, exerted through the limiting effects of stream downcutting imposed by the ground-water table. The changeover from fairly rapid downcutting in the Fagataloa-type stream gulch to lateral and

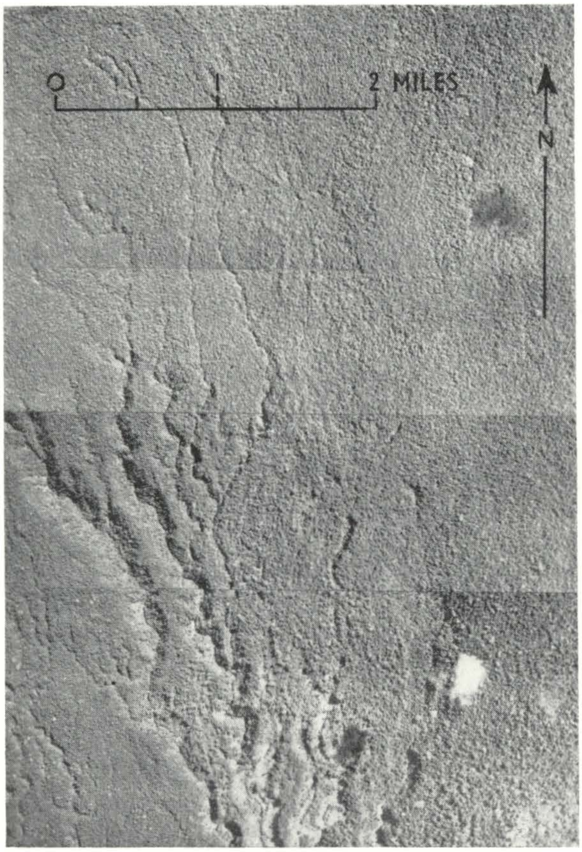

Fig. 11: Headwaters of Lata River, south Savai'i, showing contrast between undissected Paupua lava slopes (right) and Salani slopes with multiple gullies (left).

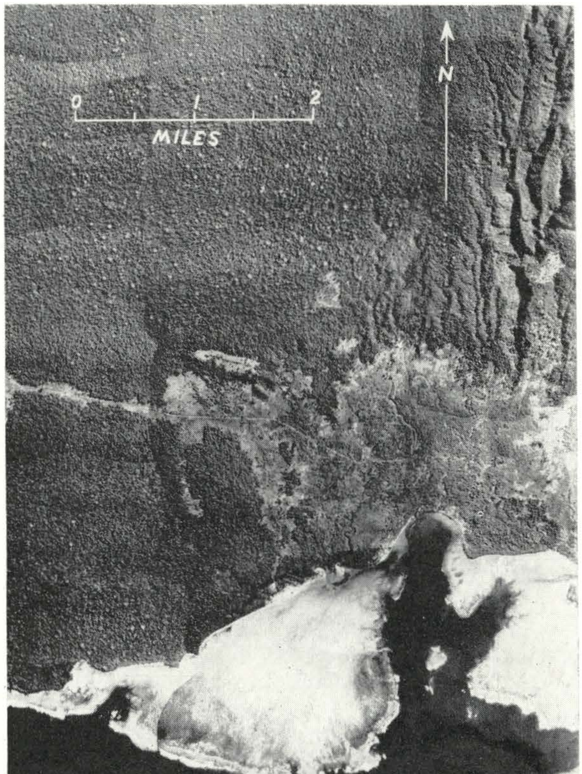

Fig. 12: South coast of Upolu about Sa'anapu village. Strong contrast in drainage and coral reefs between Salani Volcanics on right with multiple gully systems and wide reef, and Lefaga on left with no gullies and narrow reef.

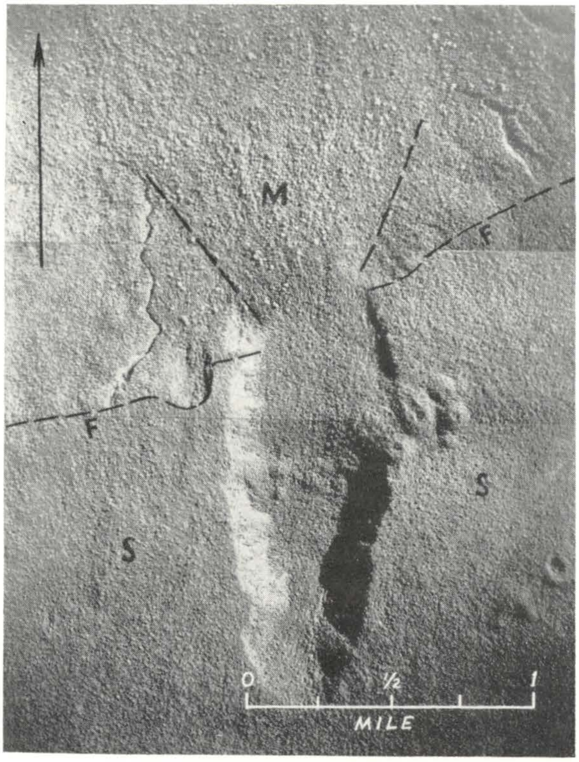

Fig. 13: Canyon on Savai'i uplands south of Sasina. The canyon has been cut in Salani Volcanics (S) which have later been downthrown to the north by a large fault (F), the scarp of which is in the centre of the illustration. Mulifanua lavas cascaded over the head of the canyon and covered the downthrown area to the north (M). Later a short chain of Mulifanua cones formed in and to the east of the canyon.

head-wall sapping by springs must occur rapidly, as soon as the stream reaches the grade locally imposed by the ground-water table, which is held up by the buried Fagaloa ridges. Once this stage is reached the canyon enlarges by spring-sapping of the walls and probably undercutting by streams of the stratified Salani flow rocks.

The canyons are obviously an early-mature stage of erosion in such a terrain, the youthful stages of which are represented by stream gulches of the Fagataloa type, and the mature stages by deep bays like Fagaloa Bay.

Although a major drop in sea level, such as occurred in the Last Glacial cooling, during erosion of the canyons, undoubtedly accelerated stream erosion, it could not have initiated canyon formation, as otherwise the canyons would be much more numerous and at all stages of development. Furthermore, they would have a deep alluvial fill, instead of the present gravel-veneered rock floor.

Alias

Shallow stream channels and gutters up to about 30 ft deep, cut in lava slopes and containing only thin bouldery alluvium, are locally termed alias (see Friedlander, 1910, p. 515). They are quite ungraded and follow the slope gradients in a series of cascades and plunge pools. During rainy weather they contain strong turbulent streams, but at other times are usually dry; very few retain pools of rainwater, and none afford a year-round water supply. Alias are common on Mulifanua and Salani lavas, less so on Lefaga, and rare on Puapua. None has yet developed on Aopo lavas.

Swamps and Alluvial Flats

A narrow, discontinuous low strip of swamp lies at the back of most Holocene beach ridges, and at the inland edge of the strip of Tafagamanu Sand bordering the coasts. The deposits are rarely more than 3 ft thick and consist of soil and fine rubble washed from the nearby basalt slopes, and wind-blown sand. Near the mouths of streams the deposits

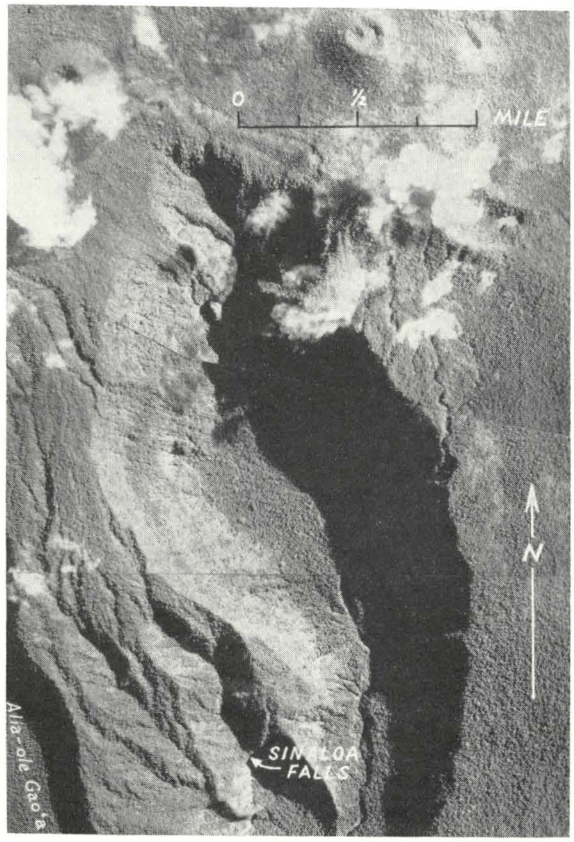

Fig. 14: Canyons on Vanu River, south Savai'i. The surrounding rocks are Salani Volcanics, with Fagaloa in the walls, alluvium veneering the floor, and a Puapua lava cascade over the left head-wall. Two Puapua cinder cones visible at top. The river channel is not cut in alluvium, but is emphasised in the photograph by an absence of trees. Water is flowing at the position of the southern edge of the photograph, but disappears beneath a dry bed a few hundred yards downstream.

are more pebbly and merge into the small deltas of mud and fine gravel laid down by the stream. Most river-mouth deposits consist of muddy gravels, which unfortunately do not seem to be suitable for use as aggregate or road metal. A few rivers (e.g., Nu'usuatia River) discharge into sheltered estuaries and bays (sheltered by spits of wind-blown sand and river-laid gravels) and are building up swampy mud flats that support mangroves and other vegetation.

Apart from small swamps in the craters of both islands, a few, more extensive, swampy areas occur on the uplands as a consequence of underlying rock structures. The most notable in Savai'i is Fusi Swamp, which occupies a broad hollow formed of converging low-angle lava slopes on the crest of the island. It is floored with a Recent deposit of grey mud on which is a dense growth of pandanus. Large areas of swamp and alluvium occur above the Fuipisia and Afulilo Falls in the Vaigafa River (eastern tributary of Fagataloa River, eastern Upolu) - see fig. 10 and pp. 23, 25.

Narrow alluvial flats 5–8 ft above sea level, underlain by brown, weathered sandy gravels, occur at some stream mouths, e.g., Lauli'i Bay. These are associated with the Tafagamanu Sand and were laid down when sea level stood some 5–6 ft higher than at present. They were not mapped separately during the work, but further search for more areas would be useful, as they appear to be suitable for use as roading gravel, and may have possibilities as concrete aggregate.

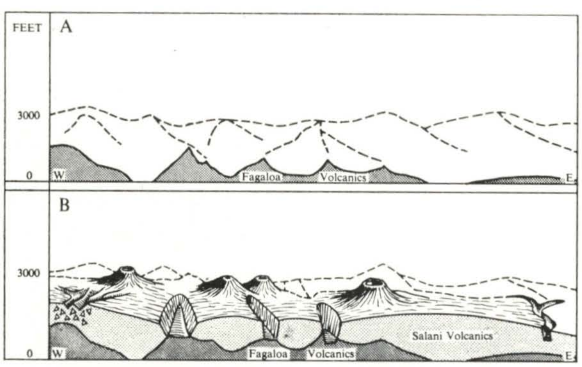

Fig. 15: Possible relationship to structure of stream-eroded forms on Salani Volcanics, south Upolu.

The largest area of alluvium is the Lalomauga Alluvium in the south branch of the Falefa River (fig. 16). A Mulifanua lava flow filled the main valley, blocked the tributary valley, and caused the stream to aggrade up to the level of the lava flow (fig. 17). Later, the stream cut down through the confining lava and degraded the alluvial deposit. A few, narrow, non-matching terraces, up to 30 ft above stream level, were formed during the degrading process.

Escarpments

A rugged erosion escarpment 300–400 ft high occurs near the crest of Upulo at the head of the Falefa River. It marks the edge of the upland Salani lava sheets that rest on the partly buried crest of Fagaloa rocks. Previously the Salani lavas were confined by a Fagaloa crestal ridge, but continued stream erosion on the north side only of the ridge caused the divide to migrate until the escarpment-forming Salani rocks were exposed.

A smooth, 500 ft step extends along the north side of the crest of Savai'i for some 20 miles from Sataua in the north-west to a point due south of Sasina. It occurs in Salani and Mulifanua basalts, is indented at the east end by a typical Salani canyon floored with Mulifanua lavas (fig. 13), has a few small cinder cones on it, and has been overflowed by Mulifanua and younger lavas (fig. 5). It is a fault scarp and, as such, is discussed further in Chapter 4.

Coastal Features

The coasts of Western Samoa are of several types, depending on the age and condition of the neighbouring rocks.

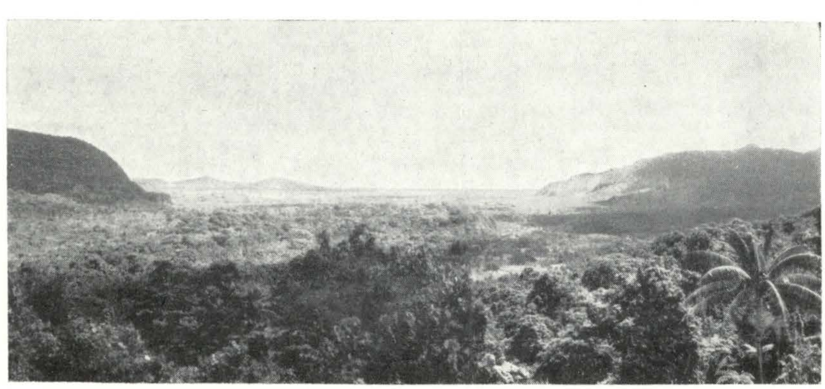

Fig. 16: South branch of Falefa Valley, from road to Tavalagi Saddle, i.e., from south. Fagaloa hills to right and left, Mulifanua basalts filling main valley in distance and to left, and impounding fill of Lalomauga Alluvium in foreground.

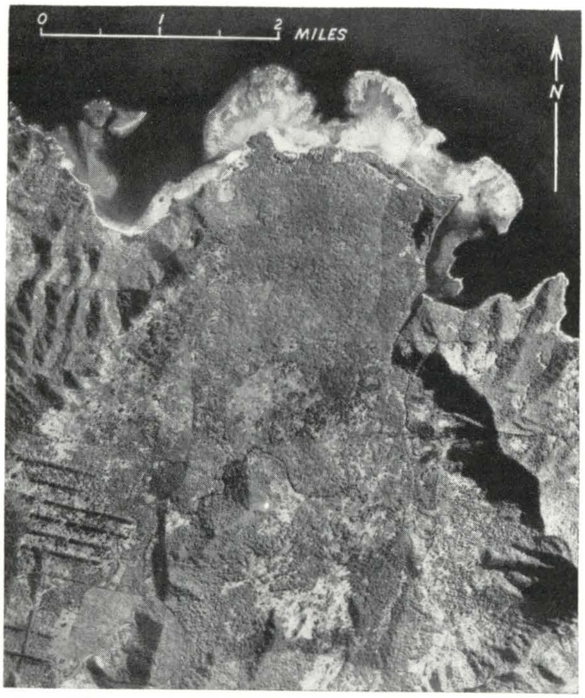

Fig. 17: Flow of Mulifanua Volcanics flooring Falefa Valley north-east Upolu (from lower left to sea), filling older valley in Fagaloa terrain (steep hills to right and left) and causing accumulation of Lalomauga Alluvium in tributary valley (lower centre). Note wide reef on Mulifanua lava fan, sparse reef on steep Fagaloa coast.

Sea cliffs are common around headlands of Fagaloa rocks in eastern Upolu and northern Savai'i and are the result of normal marine trimming since the last main post-Glacial rise of sea level. However, as described below, high coastal cliffs on Salani and Mulifanua rocks elsewhere in Upolu and in Savai'i cannot be due to marine erosion alone and must owe their origin to structural causes. A nearly vertical cliff, 100 ft high and $5\frac{1}{2}$ miles long, occurs on the south-east coast of Upolu, and has at its foot a narrow strip of Tafagamanu Sand, talus, and younger swamp deposits. A continuous narrow fringing reef lies offshore (fig. 4). Along the south-west coast of Savai'i a magnificent line of cliffs extends for 9 miles from near Falelima to Foailuga. They reach a maximum height of 250 ft between Fogatuli and Samataiuta. Near Fagafau a 200 ft cascade of Puapua lava has spilled over the cliff and built up from sea level a steep rubbly cone of aa and pahoehoe blocks.

For about 2 miles on each side of Falelima the cliffs lie a few chains back from the shore and are bordered by an irregular flat consisting partly of Puapua lava that has cascaded over the cliffs to the east.

Low-lying coasts occur chiefly around Salani and Mulifanua basalts, and are bordered by a narrow strip of coral sand, the seaward side of which is in places veneered with cemented beach sand (coquina). Along the low-lying coasts small bays occupy former hollows in the lava slopes, and the crests of the lava flows form the intervening low headlands. The latter are more likely to contain lava tunnels, or other conduits formed during the eruption, which now concentrate the emerging fresh ground water into strong tidal springs. Where strong springs emerge around such headlands, favourable conditions exist for obtaining good fresh water from shallow wells a short distance inland along the crest of the headland.

Coasts of Lefaga, Puapua, and Aopo Volcanics usually have low rocky cliffs, 10–40 ft high, with a narrow coral reef off Lefaga rocks, and none off the Puapua and Aopo Volcanics. At the ends of the cliffed sections where the lavas have spread along the lagoons, burying the former coast (fig. 18 and 19), the rocks are very blocky and have a veneer of black glassy cinder and ash formed by the hot lava exploding when it encountered the sea water. According to Jensen (1907, pp. 650–1) who witnessed the spectacular process in action, large quantities of cinders, ash, and comminuted lava were generated at the coasts where the Aopo Volcanics entered the sea.

"Where the lava flows into the sea we have what seems a minature volcano (pl. lix-lx). On the shore side an embankment of stones and cinders is formed by explosions, which occurred at the time of my visits in very rapid succession (one every two minutes), and which depend on the

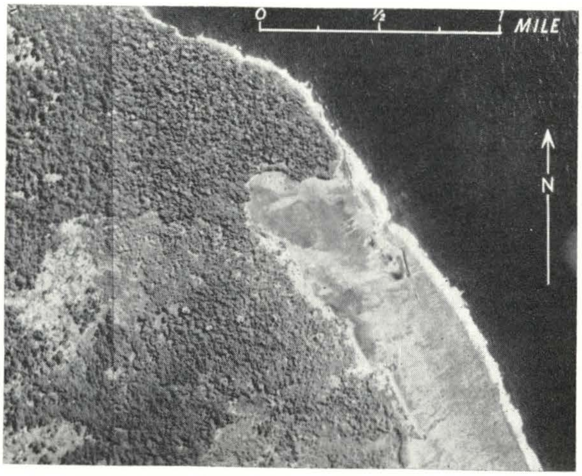

Fig. 18: Coast of Savai'i at Pu'apu'a village. Mulifanua lavas lower right, with wide reef offshore. Puapua lavas top and left, covering coral reef and forming dentate iron-bound coast.

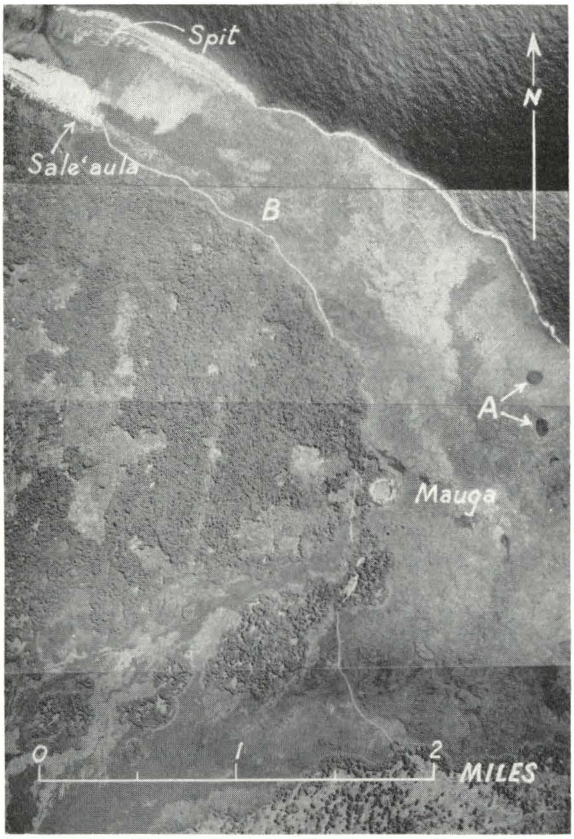

Fig. 19: North coast of Savai'i, Mauga village near centre, Sale'aula village top left. Aopo lavas from Matavanu (1905–11) filled valley (lower left) in Mulifanua Volcanics, almost buried small littoral Mulifanua cone of Mauga (centre), and flooded over and along the coral reef forming an iron-bound coast. Note the "elephant-hide" texture of the Aopo lava surfaces; the two adventitious ash rings (A); the broken nature of the lava for 1 mile south-east of Sale'aulu where it overlies the buried ridge of Tafagamanu Sand for a distance of 1 mile from Sale'aula (to B) (coconut trees grow there); and the spit of coral sand and cinders that has been built during the last 45 years.

principle of geyser-action. Immense masses of steam form, which, as shown in pl. lix–lx, rise like gigantic columns, and drift off as cumulus clouds, giving continued rains on the area over which they drift. The showers from these clouds often were salty and contained cinders, showing that matter was carried up mechanically by the steam. The roar of the rising columns was continuous, modified only by the geyser-like explosions. In the vicinity waterspouts and tornado-like whirlwinds were frequently formed. At night this spot had a glow overspreading it like the volcano itself; and on each explosion followed a magnificent firework display, probably through red-hot stones being hurled up several hundred yards.

"The cause of the explosions seems to be as follows. As the lava pours into deep water, a considerable amount of water is included in and beneath it. When the steam pressure becomes great enough, an explosion takes place.

"In March last the lava was entering the sea along a width of several miles, so that a continuous wall of steam lined the coast; and the sea was boiling hot, and in ebullition several hundred yards out. The stench from the dead coral and fishes was very bad at Matauto."

As shown in fig. 19, a long spit of cinders and coral sand has built out along the edge of the reef during the 45 years since the eruption. Also shown in the illustration are two small ash rings that resulted from explosions of the reef-covering lava. The buried ridge of Tafagamanu beach sand is shown by the presence of a strip of coconut trees and shrubs (upper left of fig. 19), which have managed to take root through the lava and cinders.

The coast on Lefaga rocks in south Upolu has a narrow wave-cut platform at the foot of the low cliffs and a narrow fringing coral reef (total width, about 500 ft). Where the coast is cliffed, the reef is wider (about 1,400 ft) and a strip of Tafagamanu Sand lies along the shore.

The cliffs in the two youngest volcanic formations have been modified but little by marine erosion, and a narrow wave-cut ledge is present only rarely. This is termed the "iron-bound" coast. In vertical air photographs, the Puapua cliffs have a finely dentate appearance, whereas the Aopo cliffs are nearly smooth in outline. Both were formed originally when the lavas spilled over the edges of the coral reef into deep water. As described by Jensen (1907, p. 654), the hot lava, on reaching the waters of the lagoon, stopped flowing seaward, and rose by new masses being thrust under and lifting the cooled surface. It then flowed along the coral reef and steadily widened until it reached the seaward edge. As it spilled over the edge it tended to preserve an almost vertical front (p. 647). In this way the later lavas, by raising the general surface of the field as much as 50 ft, gave rise to the sharp rocky cliffs seen today (fig. 5).

Emerged Shorelines

Traces of a geologically recent 5 ft stand of the sea are common around the coasts of Samoa. The strip of coral sand (Tafagamanu Sand) on which are built many of the coast villages, and which forms the few sand spits (e.g., Mulinu'u Peninsula) is the most widespread deposit from this higher sea level. On the rocky coast east of Apia, the cliffs are fronted by small rock platforms, 6–8 ft above sea level, and a few of the bays have small alluvial flats at river mouths merging with the Tafagamanu Sand. On the low rocky portions of the east, south, and west coasts of Upolu, strips of Tafagamanu Sand alternate with undulating benches of pahoehoe lava flows strewn with scattered rounded boulders up to 8 ft above sea level, and with weakly trimmed headlands higher than the 5 ft level. Similar raised beaches also occur in Savai'i, with the difference that they are commonly covered by Puapua lavas. A contact between Tafagamanu Sand and Puapua basalt is well exposed at the north end of the beach beyond Puapua village (see fig. 20).

The 5 ft shoreline is very common throughout the Pacific and elsewhere in the world, and is the result of a post-Glacial sea-level rise accompanying a phase of warmer climate. It has been correlated by Flint (1947, pp. 487–99) with a climatic optimum some 4,000–6,000 years ago; but radiocarbon analyses of raised-beach shell samples, collected 10 ft above mean sea level on the Hauraki Plains, New Zealand, and probably representing an old sea level about 5 ft higher than present, have shown an age of 2,270 ± 70 years (Ferguson and Rafter, 1957, pp. 738–9). No remains of emerged coral reefs were found in Samoa, although some parts of the barrier reefs are almost dry at low tide. Coral is exposed at low tide beneath Puapua lava at the eastern end of O le Pupu in southern Upolu. The chief objection of previous writers (e.g., Thomson, 1921, p. 64) to the 5 ft sea level was this absence of raised reef. However, MacNeil (1950) has shown that all the reefs of Okinawa except a few especially protected "pedestals", 5–6 ft high, beneath very large slumped blocks of early Pleistocene limestone, have been eroded down to or just below present sea level from the 5 ft stand. It is thus most probable that the reef flats of Samoa are erosional, having been reduced from the 5 ft level during the last 2,200 years.

Traces of a 15 ft stand of the sea were found at a few especially favourable and sheltered localities. The most widespread deposit is the Nu'utele Sand, but a more significant deposit occurs at Gataivai in south-east Savai'i. There, Puapua Volcanics are benched up to 15 ft above sea level, and at the inner margin of the bench, at the foot of low irregular

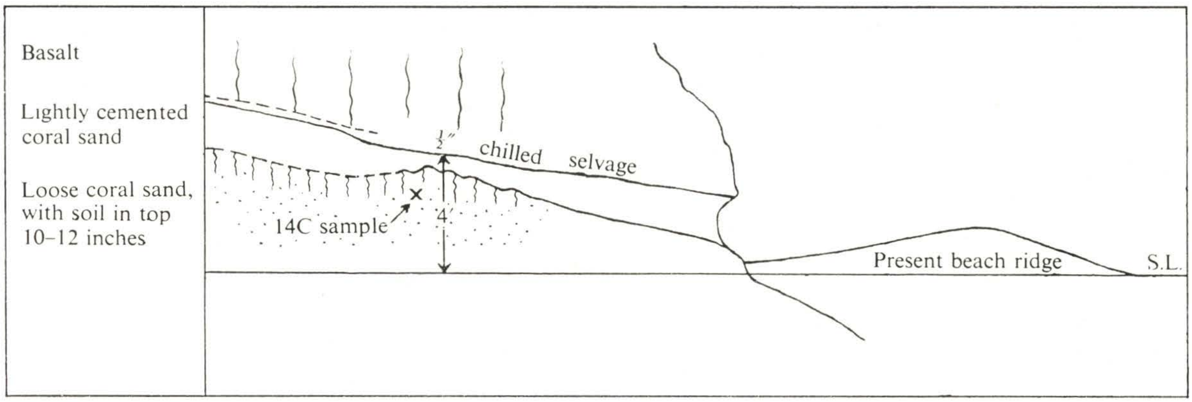

Fig. 20: Basal contact of Puapua basalt on Tafagamanu Sand, near Pu'apu'a village, Savai'i.

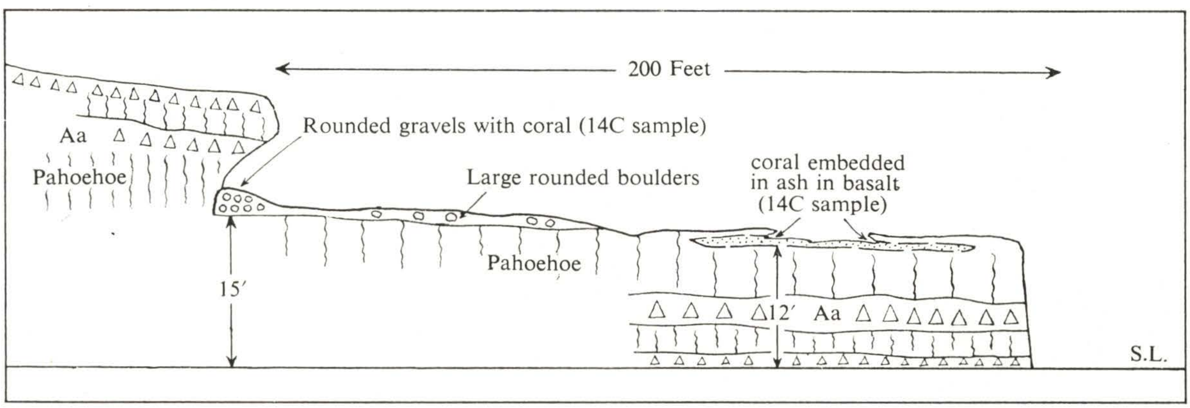

Fig. 21: Wave-cut bench and coralline ash in Puapua basalt, 15 ft above present sea level, near Gataivai village, Savai'i.

N.B.—The samples indicated in fig. 20 and 21 are under investigation for radiocarbon dating. Results will be published in *N.Z. J. Geol. Geophys.*

cliffs, is a small berm of fine, lightly cemented rounded gravel containing much worn coral (fig. 21). Also within an ash bed in the basalt of the bench, some 12 ft above sea level, are fragments of coral.

Evidently while sea level was rising towards the 15 ft level the lower basalts were erupted, reached the edge of the pre-existing reef, and some coral fragments were washed up to be incorporated with the ashy material on top of the flows. Shortly after, more flows reached the coast and at Gataivai were trimmed by wave action back to a line of low cliffs. Possibly these flows came only as far as the line of cliffs and the 200-ft-wide bench (fig. 21) is not entirely wave eroded.

Although coral samples were collected (as indicated, fig. 21) for radiocarbon analyses, they were most likely derived from the reef beneath the lowest Puapua basalts, possibly as debris from explosions of the lava on meeting the sea, and as such may not be contemporaneous with either the benching stage, or even with the oldest underlying Puapua basalt.

The 15 ft level is believed to be post-Glacial, because of its occurrence on reef-covering Puapua basalts and by correlation with benches at a similar height elsewhere in the Pacific. Similar shore lines 10–15 ft above present sea level are reported in many Hawaiian islands by Wentworth and Palmer (1925), and attributed to a very recent eustatic shift in sea level that post-dated all secondary Recent volcanism on Oahu.

On the coast of Australia four post-Glacial levels are reported by Fairbridge (1952, p. 345): 10–11 ft, 5–6 ft, 2–3 ft, and the present low-tide bench. Fairbridge concluded that the highest level was about 4,000 years old, and correlated it with the "Atlantic" phase of climatic optimum (the Flandrian stage of Dubois). However, remnants of the 15 ft sea level exist in Westland, New Zealand, and radiocarbon analyses give an age of 4,600 years (Fergusson and Rafter, 1955). Thus, the bench at Gatavai was presumably cut and the Nu'utele Sand deposited during the post-Glacial Thermal Maximum.

Possible evidence of a 30-ft-high sea level is to be found in the Vini Tuff (see p. 47), but the precise age is not known, and can only be inferred to be late in the Last Interglacial.

Evidence of older high sea levels is scanty and is found in small, vague remnants of coastal benches on Fagaloa rocks south-east of Falelatai, and near Fagaloa Bay. Their heights were not accurately measured but are greater than 130 ft and possibly nearer 200 ft. They could be traces of a Tyrrhenian (Last Interglacial) high sea level (110–130 ft) or possibly a Milazzian level (220–240 ft) of the Penultimate Interglacial.

Outlying Islands

With the exception of Manono Island, which is a low lava cone, the small outlying islands are steep and either arcuate or circular in form. They represent the remains of tuff cones that were built by shallow submarine eruptions. Apolima Island still retains the original circular form, and probably much of the original crater wall and fill (fig. 29). The outer coast of the island has been steepened and cliffed considerably by marine erosion, so that none of the original outer slopes of the cone remain. From the comparison with the similar but much younger tuff cones of Tafua savai'i it seems probable that the Apolima cone may once have been very much larger.

Reefs

Stearns' (1944, p. 1320, 1324–6) useful account of the reefs of Upolu and Savai'i is considered below in the light of the formational nomenclature used in this bulletin. Fringing reefs range from narrow shelves to flats 1½ miles wide (e.g., at Lefaga Bay). They consist of coralline sand, shells, and other detritus, with coral heads bound together by coralline algae at the outer edge. Most of those not enclosed by a barrier reef lie along the south coast of Upolu.

A striking relationship exists between the barrier reef and the age of the rocks. No living barrier reef and scarcely any fringing reef occurs along coasts of Fagaloa rocks, wide reefs are found off coasts of Salani and Mulifanua rocks, and little or none off Lefaga and younger rocks. Futhermore, off coasts of Salani and Mulifanua rocks, the reefs tend to be of the barrier type where landward lava slopes are gentle, and of the fringing type where the lava slopes are steeper.

The main barrier reef of Upolu is nearly continuous from Vailele Bay to the west of the island, around Manono Island, thence along the south coast to a point opposite Sama'i. A short barrier reef lies at the east end of the island also. Remnants of a barrier reef occur on the south shore, but much of the reef has been covered with Lefaga and Puapua Volcanics, or else has subsided below sea level, near Cape Tapaga.

A wide barrier reef 14 miles long, and a fringing reef, lies off the east coast of Savai'i (Fa'asaleleaga), a narrower one occurs off the north coast, opposite Safune, and a third one lies off 'Auala in north-west Savai'i. The ends of all these reefs are buried under either Puapua or Aopo Volcanics. Nearly all the remainder of the coast of Savai'i is reefless and much is rock bound. Originally Savai'i was surrounded by a much more extensive barrier reef, which has since been buried by the younger lavas. Flats of reef-covering Puapua lava extend along the south coast west of Taga, and east to Satupa'itea. Another broad area of Puapua lava covers the barrier reef between Palauli and Fa'asaleleaga, but a large part may be built out far beyond the edge of the barrier. The original extent of the barrier was probably from near Taga in the south, all round the east and north coasts to Fagasa in the north-west.

Submarine Features

Apart from the general bathymetry of Samoa, that in Apolima Strait and along the north coast of Upolu to as far as Saluafata Harbour has been charted in detail by the survey ship HMNZS *Lachlan* (see Map 3, in the pocket at the back of this bulletin).

Isobaths off the north coast of Upolu show a simple submarine terrain, with a wide shelf opposite Apia, sloping gently from a little less than 30 fathoms down to 45–50 fathoms, then a relatively steep slope down to at least 500 fathoms. The shelf is much narrower north of Cape Fale'ula, and instead of the coral reefs dropping off into 10–20 fathoms, there is in places a continuous slope from the outer edge of the reefs down to and beyond 500 fathoms. Elsewhere around Upolu Island (and also around Savai'i and Tutuila) a wide shelf at depths of 80–100 fathoms lies below the 40–50 fathom shelf, and at its outer edge drops away to depths of over 500 fathoms.

In contrast to these shelf conditions, the bathymetry of Apolima Strait shows a remarkably complex terrain, with the 40–50 fathom and the 80–100 fathom shelf-levels well in evidence. The shelves surrounding Upolu and Savai'i Islands join across the strait near Apolima Island in a broad flat some 3 miles wide and 30–40 fathoms deep.

North-east of this flat is a north-east-trending elongated basin with a flat floor at 70 fathoms and moderately steep walls, the rims of which are sharply defined at 40–50 fathoms. A similar basin lies south of Apolima Island, but trends south-east and has a flat floor between 75 fathoms at the north-west and 80 fathoms at the south-east.

Beyond these two elongated basins, to the north-east and south-west lie two strikingly steep-walled, roughly circular basins. They are flat-floored, at depths of 80–100 fathoms. One, that to the south-west, has been entirely surveyed and shown to be completely enclosed. It seems probable that the other, and possibly two more incomplete features to the east and south-east, are similarly closed.

On the flat-topped ridges separating the basins are a few indistinct hollows and small irregular but compact hillocks. Some of the hollows border the barrier reef of eastern Savai'i, at depths of 42–45 fathoms with a small low at 50 fathoms half-way between Apolima Island and Fa'asaleleaga. The hillocks appear to occur in random fashion, with one of 20 fathoms relief a mile west of Apolima, another of 25 fathoms relief two miles to the west-north-west, and a number along the 20–30 fathom isobaths to the north-west. A few small hillocks lie three miles north of the Mulifanua coast, and a large one of 20 fathoms relief lies $6\frac{1}{2}$ miles north-north-west of the coast.

To the south-west of Apolima Strait, the sea bed falls away from the 45 fathom shelf in a remarkably steep, fairly straight slope, the angle of which is between 40° and 45°. The slope lessens at about 450 fathoms and continues down to and beyond 600 fathoms as a gently sloping bench. At the inner edge of this bench is a small, remarkably deep (100 fathoms) closed basin with a lip at or less than 545 fathoms.

In interpreting the bathymetric map, certain assumptions have been made, the most important being that the ridge and basin forms are constructional not erosional. If these features are constructional they are almost certainly coralline rather than volcanic.

The flat basin floors at 90–100 fathoms are considered to be remnants of an old platform, partly wave cut, partly depositional, on which younger reefs grew. The steep slope with the 500–600 fathom bench, south-west of the strait, may be the original seaward, reef-veneered face of this old platform built up from a still older platform at the 500 fathom level. On the other hand the slope may be a fault scarp across which a segment of the platform sank from 100 to 500 fathoms. At the north-west end, a part of the slope swings almost due north for a mile, and from 50 to 200 fathoms increases in steepness to about 70°. This part is most probably a fault scarp.

The other deep basins have undoubtedly been partly filled with sediments, raising the floors to less than 90 fathoms. The floor of the elongated basin south of Apolima has a gentle slope towards the open south-east end, while that of the shallower one north of Apolima has several low broad ridges rising to 50–35 fathoms that appear to be banks of sediments accumulated parallel to the main south-easterly current through the strait.

The meagre bathymetry of north-eastern Upolu shows that a 100 fathom bench cuts across the Fagaloa Volcanics, indicating that the bench is the younger. Although more information is desirable (such as profiles in and out of Fagaloa Bay), the 100 fathom platform in Apolima Strait, and the bench around the islands elsewhere, is correlated with the low sea level with which was associated the deep erosion of the Fagaloa terrain and is probably early Pleistocene in age. Both the platform and the Fagaloa coasts are drowned.

Resting on the 100 fathom platform are steep-sided forms interpreted as drowned reefs (250–300 ft high) that have been planed off at depths of about 45 fathoms. The reefs in the strait show a remarkable resemblance to the closed circular basins of atolls. Around the islands they appear to have been barrier reefs. They are probably highly complex in structure and consist of increments of widely different ages. The younger increments were probably added during the 45 fathom stand of the sea, which is correlated with the maximum of the Last Glaciation. Accordant rises on some ridges suggest a later stand of sea level at about 25 fathoms. At some time after the 25 fathom stand, small marine or littoral tuff cones erupted around the lower shore lines of Savai'i and Upolu to form the small hillocks described on p. 32, and a larger one appeared 6½ miles off the Mulifanua coast. Also, flows of Salani to late Mulifanua basalts undoubtedly buried the shoreward areas of the 45 fathom bench before and during the low sea level of the Last Glaciation, and very probably gave rise to the small tuff cones on meeting the sea at the lower levels. This is particularly evident along the west side of the strait, where a series of shallow hollows at 40–45 fathoms represent the Last Glaciation bench, with a few remnants of the 25 fathom reef along the outer edge, and the landward slopes are probably Mulifanua Volcanics on which are located several of the drowned tuff cones.

The rise of sea level from the 45 fathom to the 25 fathom level within the Last Glaciation was sufficiently rapid to drown many of the reefs, and the later post-Glacial rise was so rapid as to drown the few isolated remnants. Shoreward reefs resumed growth when the rate of sea-level rise decreased, grew from depths of at least 20 fathoms to slightly above present level, and during the last 4,000 years have been planed back to present sea level.

CHAPTER 3—STRATIGRAPHY AND PETROLOGY

Introduction

The main divisions of the volcanic and sedimentary rocks are shown in Table 4, and the typical occurrences are described below. The subdivision of the rocks is based on age differences, and for the typical occurrences of the volcanic formations these are obvious. However, away from the typical localities, difficulties in mapping were inevitable, since it is highly probable that rocks exist that are intermediate in age between the "types" of the main division. Even so, the writers believe that, although some amendments to the map may later be necessary, they will not greatly affect the sequence or structure shown.

The six major volcanic formations described below are as follows, the youngest at the top:

	Aopo Volcanics
Holocene	Puapua Volcanics
	Lefaga Volcanics
- - - - - - - - - - - - - - - -	Mulifanua Volcanics
	Salani Volcanics
Pleistocene	
- - - - - - - - - - - - - - - - - -	Fagaloa Volcanics
Pliocene	

Four other rock units are included in Table 4. Of these only the Vini Tuff is volcanic, but it differs from the major groups given above in that it forms marine tuff rings rather than terrestrial flows and pyroclastics. It may be older than the Salani Volcanics, but is almost certainly younger than the Fagaloa Volcanics. In the descriptions that follow it is considered under the general heading of "Marine Tuffs and Sedimentary Rocks". This conveniently differentiates it from the majority of Samoan volcanic rocks, which differ from it considerably but from one another in little other than the effects of age.

Of the truly sedimentary rocks, two formations, the Nu'utele Sand and the Tafagamanu Sand, represent raised beach deposits that were probably contemporaneous with the Puapua Volcanics. Older raised beaches and even raised reefs may well be present locally below a younger cover of basalt and scoria. None was found, although coral was reported from the bottom of the Afia well. Alluvium is seldom noted on the maps since it commonly occurs only as valley fills too narrow to map, or as a thin sheet that would cover wide areas of the map and would mask the underlying geology. One large area of thick alluvium (the Lalomauga Alluvium), however, was formed in the valley of a tributary to the Falefa River that was blocked by a flow of Mulifanua age. This alluvium was therefore probably contemporaneous with the Puapua Volcanics.

Cone Deposits

The cones consist of a wide variety of volcanic debris, of all grades. The few sections of lava cones that were examined contained thin pahoehoe flows with thicker, grey and black clinkery aa and, rarely, brown weathered ash layers. Cinder cones contain various incoherent mixtures of coarse and fine, red, grey, and black cinder, and brown ash with and without basaltic breccia. Finer deposits are commonly slope-bedded with moderate dips, or subaerially deposited with thin sub-horizontal bedding.

A remarkable section through a cinder cone may be seen in a quarry just south of the highest point of the road across the base of the Falealupo Peninsula, in north-west Savai'i. Well graded, bedded, red and purple cinders there reveal several local unconformities, and some of the coarser beds include vesicular spinous and slaggy bombs of grey blotched glassy rock. Similar red cinder occurs at Tuialemu near Cape Tapaga (south-east Upolu), but has been welded into a tough rock that can be broken into blocks only with difficulty. The lower 2 ft of the cinder bed consists of contorted ropy fragments up to 1 ft long, the products of fire-fountaining, that became welded together while still plastic.

The most completely preserved tuff cone is Tafua savai'i, a double-cratered cone in south-east Savai'i It consists of faintly slope-bedded compacted brown tuff, with small blocks of porous basalt, scattered at low levels, and thin flows and basaltic breccia higher up. The inner walls of the two craters consist mainly of a larger number of thin sill-like basaltic flows. The basal tuff beds are exposed at Tafua village, and rest on an undulating surface of young pahoehoe basalt mapped as Puapua. A finely laminated, presumably fluviatile-bedded, locally cemented, breccia of basaltic and brown tuff fragments fills the larger hollows in the underlying surface. No coral fragments or marine shells were seen, such as were found in the Vini Tuff, although the basal beds are only some 12 ft above present sea level, and the cone is probably late Puapua in age.

Two small low cones occur on the flat of Aopo lava near Mauga village, Savai'i (A in fig. 19). They resulted from the explosions of trapped sea water through the lava, and consist of much comminuted lava fragments and fine black cinder.

The density of volcanic cones in space, and of volcanic eruptions in time, are both discussed on pp. 49–50.

Major Volcanic Formations

Fagaloa Volcanics

NAME

Fagaloa Bay lies near the eastern end of the northern coast of Upolu, 20 miles east of Apia.

DISTRIBUTION

Fagaloa Volcanics extend, with only minor coverings, over the whole of the north-eastern quarter of Upolu (from Apia eastwards). They are also present in the deepest valley bottoms in southern Upolu. They form the buried hills south of Magia, and the hilly country between Falelatai and Lefaga Bay in south-west Upolu. In Savai'i more doubtfully, the rocks south-west of Fagamalo and at the bottom of the deep gorges in the south-central region (e.g., Vanu River) are also referred to this group.

SURFACE EXPRESSION

The Fagaloa rocks, being the oldest in Western Samoa, are the most eroded. They form steep weathered slopes with sharp ridges that locally stand above the level of the surrounding basaltic plateaus (fig. 17). Two somewhat different landforms can be recognised.

The one, possibly the older, has no part of the original cone form remaining and forms steep high mountains, with slopes of up to 50°, rising as inliers above the gentle slopes of the later lavas. It includes dykes, which form bold vertical cliffs and steep narrow ridges, often several hundred feet high. Dykes at Afulilo Falls strike 280° to 290°, dip 80° to 90° N; those at Fagaloa Saddle are vertical and strike 160° to 190° (fig. 22); and those at Soaga Falls strike 40°, dip 30° NW. Maugafolau Hill, south-west of Apia, has been eroded almost to the stage of a volcanic plug.

The other landform, though steep locally, includes ridges that descend gently seawards and could be the surviving parts of the original cone surface. Some of these gently sloping ridges have narrow flat tops, on which the soil is strongly leached, acidic, and now supports little more than wiry grass (fig. 4).

The steep topography continues to the coast, where there are commonly rugged cliffs, and descends rapidly into relatively deep water close to the shore (fig. 17). The steep offshore slope has prevented the formation of coral reefs over much of the Fagaloa coastline, and where a reef is present it is fringing, close inshore.

Fagaloa Bay itself strongly resembles a drowned valley (fig. 9), and is probably graded to the 100 ft

Fig. 22: Basaltic dykes in weathered Fagaloa tuffs and flow rocks, along new road on west side of Fagaloa Saddle.

Fig. 23: Lauli'i Quarry, north-east Upolu, showing Fagaloa rocks. The two massive beds are pahoehoe flows, which grade up into beds of aa. A third bed of aa crops out at the base of the quarry. Each pahoehoe flow has a sharp contact with the next underlying bed of aa (visible on right).

submarine bench shown on charts off the coast of Apia.

LITHOLOGY

The formation consists of intercalated aa and pahoehoe flow rocks, rubbly scoria (commonly weathered red), brown ash beds, thin vitric tuffs, and contemporaneous basaltic dykes (fig. 22). The flow rocks characteristically contain large (up to 1 in. long) pale green olivine phenocrysts or nodules, with well developed prismatic cleavage, that weather to a golden brown colour. Near Alaoa power station, peridotite inclusions are particularly abundant as small xenoliths.

The flow thicknesses range from a few inches to 100 ft. Most flow members grade up from a glassy base through more vesicular and porous rock to the next overlying bed of scoria and aa, which is two to four times as thick. The lower contact is usually sharp (fig. 23). The dyke rocks, which are restricted in Western Samoa to the Fagaloa Volcanics, are similar to those of the flows, but have their vesicles better aligned. On the saddle of the Fagaloa road overlooking Fagaloa Bay, for example, the vesicles are aligned in the plane of the dyke, which strikes slightly east of north, and are elongated so that they dip at about 30° northwards. The rocks exposed below Salani Volcanics in the bottom of the deep gorges of the Vanu River area have no correlatives elsewhere, some being apparently andesitic in character. They have provisionally been placed in the Fagaloa Volcanics.

Jointing in the denser rocks is variable. Platy jointing, though rare, serves to distinguish these rocks from those of all younger groups (fig. 24).

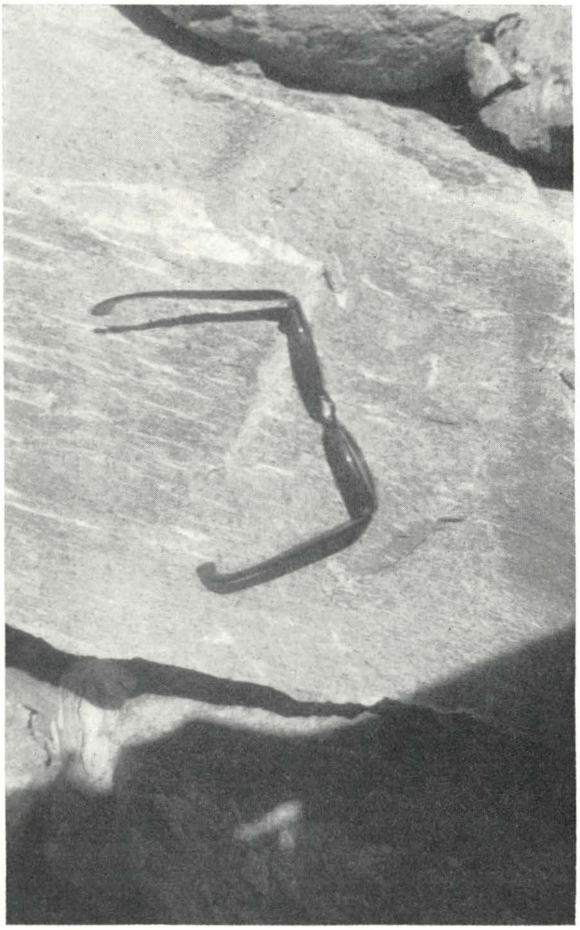

Fig. 24: Platy jointing in Fagaloa olivine basalt at Laulii Quarry, north-east Upolu. The joints have a fine light-grey powdery coating.

PETROGRAPHY (by R. N. Brothers)

The distribution of rock types examined in thin sections is listed in the Appendix, together with locality and collection numbers. Reference to specimens is made here by numbered thin sections, which are filed in the petrology collection of the New Zealand Geological Survey, Wellington.

The Fagaloa formation includes a wide range of rock types, from picrite to olivine basalt, feldspathic basalt, hornblende andesite, and trachyte. In this respect the Fagaloa rocks are more diversified than any other group of lavas in Western Samoa and the apparent degree of magmatic differentiation attained in Fagaloa time greatly exceeds that displayed by post-Fagaloa flows and dykes. Nevertheless, it is of petrogenetic interest to note that the more basic basalts of picrite type are poorly represented in the Fagaloa group, but are quite common in the overlying younger lavas.

Picrite basalt has been collected only as gravel in the bed of Vanu River and there is some doubt if the pebbles belong to the Fagaloa Volcanics, although MacDonald (1944) has described similar rocks *in situ*, from localities now mapped within this volcanic formation at Lauli ʻi Bay and Maʻasina on Fagaloa Bay. Thin section 16655 contains abundant phenocrystic olivine and microphenocrystic titaniferous augite in an intergranular mesostasis of ilmenite and magnetite, pyroxene, accessory apatite, and rare patches of brown glass. Laths of acid labradorite form less than 5 per cent of the groundmass. Two distinct types of olivine are present: euhedral crystals showing only slight resorption; and anhedral grains, often with translation lamellae and undulose extinction, which have resorbed edges characteristically bordered by large magnetite crystals.

The pilotaxitic *feldspathic basalt* of thin section 16627(3) lacks olivine but contains abundant labradorite; equally rare in occurrence is the *aphyric basalt* of 16629(1) in which phenocrysts are absent, the rock consisting of a fine-grained hyalopilitic mesh of feldspar (An_{40}–An_{62}), pyroxene, iddingsitised olivine, and ores.

Olivine basalt is the commonest rock in the Fagaloa Volcanics. Olivine invariably is phenocrystic as large euhedral crystals commonly replaced to some degree by iddingsite or marginally resorbed with a corona of small iron-ore granules. Pink titaniferous augite occasionally reaches phenocryst size, sometimes in glomeroporphyritic clots with ilmenite, e.g., 16627(2), but the pyroxene usually occurs as abundant microphenocrysts in the groundmass. Large laths of feldspar are rare and when present with phenocrystic pyroxene are ophitically enwrapped, e.g., 16627(1). Groundmass textures vary from intergranular to pilotaxitic and intersertal, with some small patches of acid, low-index glass in the holocrystalline rocks (16630). In addition to microphenocrystic titanaugite, small crystals of diopsidic augite are sometimes common in the groundmass, e.g., 16633(2), together with magnetite euhedra and ilmenite in rods and granules. Feldspar laths cover the range An_{70}–An_{45}, while rare small pockets of late-crystallised feldspar with refractive index greater than balsam, $2V_Z = 10°$ to $30°$, and low birefringence are classed as potassium-oligoclase, e.g., 16633(2). The accessory apatite in these rocks is often included by the K-oligoclase. The only *dolerite* (16632) sectioned from the Fagaloa Volcanics has a mineral assemblage close to that of olivine basalt, with subophitic titanaugite enclosing plagioclase, and with rare flakes of deep brown biotite.

Hornblende andesite, or trachyandesite, occurs in a dyke on the new road to Fagaloa Saddle. The rock (16631) has an even holocrystalline trachytic texture, with phenocrysts of brown hornblende seated in a felt of well formed small plagioclase laths (An_{45} – An_{30}). The quantity of alkali feldspar present was judged at less than 10 per cent. Accessory minerals include magnetite, ilmenite, apatite, and rare grains of green pyroxene.

Anorthoclase trachyte, 16655(2) from gravels in the bed of Vanu River, is characterised by phenocrystic sanidine, anorthoclase (common) and, rarely, plagioclase in a strongly trachytic groundmass of potash feldspar laths, magnetite, and aegerine-augite. A *trachyte*, 16624(1), from the dam below Alaoa power station, has a much higher ferromagnesian content; prismatic crystals of aegerine-augite and brown hornblende form phenocrysts together with large euhedra of magnetite. The groundmass contains microphenocrysts of sodic plagioclase and abundant small tabular grains of potash feldspar, as well as microglomeroporphyritic clots of green pyroxene and iron ore. Small patches of silica-rich yellow glass, with low refractive index, are rare.

Olivine nodules are fairly common in the picrite basalts and the olivine basalts. Harzburgite fragments are present in 16626(2) and 16634, the latter rock in addition containing dunite nodules.

A welded *vitric tuff* from Soaga Falls, 16633(1), contains a small quantity of olivine fragments, largely altered to iddingsite, and abundant vesicular shards of yellow-brown basalt glass which, with high index of refraction, does not appear to have been hydrated to palagonite. The absence of calcite and zeolites, and the presence of unfilled vesicles, appear to be distinguishing features between this Fagaloa tuff and the Vini tuff described later.

Age

The Fagaloa rocks are the oldest in Western Samoa. Volcanic cones of a similar degree of erosion would be classed as lower Pleistocene or Pliocene in age in New Zealand (Kear, 1957). In the tropics, erosion may well have been faster, and the rocks may be comparatively younger. They are unlikely to be older than Pliocene, however. They were tentatively regarded as Pliocene or early Pleistocene by Stearns (1944, p. 1320), who correlated them with the post-caldera lavas of the Pago volcanic series of Tutuila.

Their younger age limit is given by the facts that the Fagaloa are older than the Salani Volcanics and the oldest of the latter are presumed to have survived one glaciation. The very considerable difference in erosional form between the Salani Volcanics and the rocks around Fagaloa Bay suggests that the Fagaloa rocks there have probably been subjected to considerable erosion accompanying low sea levels associated with at least two glaciations (i.e., that the oldest Fagaloa rocks are older than the Penultimate Glaciation in age). South-east of Falelatai and near Fagaloa Bay, benches have been cut on top of Fagaloa rocks. Rough measurements showed their height to be greater than 130 ft, and quite possibly nearer 200 ft. This would date the rocks as pre-Tyrrhenian (sea level 110–130 ft) and possibly pre-Milazzian (sea level 220–240 ft).

For want of more evidence in Western Samoa, Stearns' correlation with the post-caldera Pago Volcanics is followed, and the age of the Fagaloa Volcanics considered to be late Pliocene or early Pleistocene.

Salani Volcanics

Name

Salani village, at the mouth of the large Fagataloa (or Salani) River, is on the south coast of Upolu, 12 miles west of the extreme eastern point (Cape Tapaga).

Distribution

The Salani Volcanics are widespread in Upolu, forming most of the south-eastern quarter of the island, and extending southwards over a wide area from Apia to the Vaie'e Peninsula on the south coast. A great deal of the eastern half of Savai'i is formed of Salani rocks, which are exposed, for example, in the gorges of the Vanu River, north of Sili, around Vaiola, and south and east of Ologogo (Wetzell's) Plantation. The rocks of west Savai'i are classified largely as Mulifanua, but the age difference from the Salani rocks of the east is probably small.

Surface Expression

Salani Volcanics consist of low-angle flows that can frequently be traced to their origins in craters and cones which are still easily recognisable as such (fig. 4). Lano-o-moa and Lanotai are the sources of flows in the Aleipata area, for example, and a small cone 3 miles west-north-west of Tuasivi is the source of the Salani rocks locally in that area. Cones of Salani age are frequently breached on at least one side, and even relatively perfect cinder cones are sufficiently sealed with weathered material to contain swamps in their craters (e.g., Lanotai in Aleipata). All rocks are deeply weathered, and the relatively few boulders that are scattered on the ground surface frequently show onion-skin weathering. The soil is usually over 12 in. thick. Gorges may be cut deeply into Salani rocks (fig. 13 and 14) (e.g., Vanu River, Savai'i, and Fagataloa River, Upolu) and some have been filled by a younger lava flow. Valleys are a common feature in Salani rocks, and serve to distinguish them immediately when seen from the air (fig. 11 and 12). In many places they carry water almost permanently, but elsewhere water may be absent from the dry valleys (alias) for most of the year.

In the Fagataloa River and Aleipata areas of Upolu a few individual flow margins can be plotted on air-photographs from associations of changes in slope, bouldery soil, and waterfalls in large rivers.

It is usual for the barrier reef to be far offshore where Salani rocks are present at the coast. At a few places, such as the eastern part of the south coast of Upolu, where the rocks have been severely cliffed, the reef is close inshore (fig. 4). Near Vavau in south-east Upolu the large sinkholes near the coast were probably formed by the enlargement of coastal blowholes.

Lithology

Salani flows consist of fine-grained grey-black porphyritic basalt at the base, which grades upwards through vesicular basalt to rubbly aa. The normal thickness of flows is not well known but is presumed to be of the order of a few feet. The more weathered nature of the outcrops and the presence of a few large, pale green olivine phenocrysts (like those that are common in Fagaloa rocks) serve to distinguish these rocks from the lithologically similar, but younger Mulifanua basalts.

Petrography (by R. N. Brothers)

The Salani Volcanics contain a restricted suite of picrite basalts, and olivine dolerite and basalts, most of which show to some degree the effects of zeolitisation and other late-stage deuteric alterations. In some cases extensive replacement of feldspar by analcite has warranted the use of the term analcite basalt.

The *picrite basalts* always contain phenocrystic olivine, often strongly resorbed, e.g., 16613(1), and commonly rimmed or pseudomorphed by iddingsite; the two types of olivine described in the Fagaloa picrite basalts are present in these Salani rocks. Phenocrysts of pink pyroxene occur in 16613 and 16614, as well as occasional crystals of feldspar (An_{60}–An_{45}). Intergranular groundmass constituents are magnetite and ilmenite, apatite, small crystals of titanaugite, which are abundant in 16613, occasional olivine, and rare laths of labradorite. Small scattered pockets of glass, with low refractive index and cloudy appearance, are probably palagonitic in composition. Patches of zeolites are widespread in the rocks and in 16612(3) numerous vesicles are filled and margined by layered chabazite and heulandite.

Olivine basalts form more than 50 per cent of thin sections from the Salani Volcanics. Phenocrystic euhedral olivine invariably shows some degree of alteration to iddingsite and in 16610 complete pseudomorphism has occurred. Zoned pink titanaugite is the commonest of other phenocrysts, but this pyroxene rarely attains the size of olivine crystals and is most often found as microphenocrysts in the groundmass. In this respect 16616(2) is unusual for it contains glomeroporphyritic clots of olivine and of feldspar with subophitic pyroxene. Groundmass textures vary widely in the amounts of basaltic glass present; for example, the vitrophyric rock 16616(1) contains only olivine and glass, while others grade through hyalopilitic (16612), to pilotaxitic (16610), and intersertal (16617). Titaniferous and diopsidic augites are abundant in the groundmass and usually are associated with ilmenite and magnetite. Feldspar laths, zoned and twinned, have a range in composition from basic to acid labradorite; apatite is a constant accessory. Interstitial patches of K-oligoclase are fairly common, e.g., 16617, and in 16637 contain a plexus of late crystallised olivine and ilmenite rods. With the development of coarser textures the intergranular olivine basalts pass over into *dolerites*, a change which is characterised by the appearance of large skeletal crystals of ilmenite, pyroxene coronas on olivine, and subophitic texture; the accompanying interstitial K-oligoclase patches in some cases are quite large, e.g., 16646(1).

In most of the rocks of the Salani formation there are traces of intersertal zeolite development, but three basalts are outstanding for analcite content: 16612(2), 16645, and 16646(2). In these rocks, olivine as phenocrysts and as groundmass crystals shows extensive deuteric replacement by iddingsite which, in 16612(2), has reached complete pseudomorphism. Analcite occurs as an alteration product in the cores of plagioclase feldspar laths and as an irregular groundmass constituent.

Relation to Older Rocks

Salani rocks are differentiated from the Fagaloa Volcanics by their much less weathered nature (boulders appear on the ground surface above them), by the less eroded landform (sectors of the original cone surface can be recognised, and craters are preserved), by the absence of dykes, by the less common occurrence of the large olivine nodules and phenocrysts, by the absence of andesites and trachytes, and by the fact that a reef is normally developed well offshore from a Salani coastline.

The Salani lavas occupy valleys in the Fagaloa rocks in eastern and northern Upolu, elsewhere they overtop Fagaloa ridges and partly or completely bury the old terrain.

Near the Alaoa power station, Salani rocks can be seen overlying the old reddish soil horizon formed on the Fagaloa rocks (fig. 25). Clearly a substantial break exists in this section below the Salani rocks. Generally speaking the Salani and younger lavas are somewhat distinct petrologically from the older Fagaloa rocks, and this fact is taken to imply a break in an otherwise relatively continuous sequence of volcanism. Hence the pre-Salani erosional and weathering break is thought likely to extend throughout the Territory.

Age

Coral is presumed to have grown upon Salani rocks in the Afia well and eastern Savai'i areas;

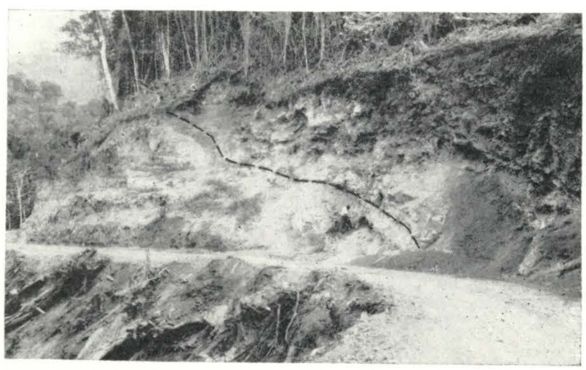

Fig. 25: Road-cutting above Alaoa hydro-electric station, Upolu. Salani Volcanics, above, rest on a reddish soil horizon developed on Fagaloa Volcanics.

and this coral is presumed to be older than the Last Glaciation (see discussion under Mulifanua below). It might well have grown at the time of the sea level, 30 ft higher than present, of which the Vini Tuff shows sedimentary evidence. Thus some Salani rocks must be Last Interglacial or older. Not even the most eroded of them (e.g., in the Vanu River gorges), however, shows evidence of more than one period of erosion due to lowered sea level, and therefore none is presumed to be older than the Penultimate Glaciation.

It is possible that the high sea level denoted by coral growth on Salani rocks and by the Vini Tuff represents an interstadial within the Last Glaciation rather than the Last Interglacial itself. If so the oldest Salani rocks would be of Last Glaciation age. An interstadial sea level of 30 ft seems unlikely however, and a maximum age of the Penultimate Glaciation is preferred.

The time boundary between Salani and Mulifanua rocks is quite arbitrary. A major difference between the two groups is the presence of deep gorges in some of the former. These were probably cut most vigorously during a lowered sea level of the Last Glaciation, and therefore the time boundary between the two groups may be placed as some time previous to the last major lowering of sea level of that glaciation.

Mulifanua Volcanics

Name

Mulifanua is a village in north-western Upolu, 20 miles west of Apia, from which ferries run to Savai'i.

Distribution

In Upolu the Mulifanua Volcanics are exposed over most of the western 7 miles of the island, and thence in the northern coastal area almost as far east as Apia. One large basalt flow that reaches the sea at Falefa is also referred to this group. On Savai'i these rocks constitute most of the western part of the island, and are present in the eastern half near Fagamalo and Tuasivi. In the latter area their distribution in a narrow strip at the foot of Salani basalt slopes suggests that they flooded over an old coral reef of post-Salani age.

Surface Expression

Dry shallow valleys and gullies (alias) occur in Mulifanua rocks, but flowing water is rare. The rocks consist of almost uneroded flows descending from well formed cones, all rocks being weathered to a moderate degree. Boulders are more common about the surface than is the case with Salani rocks (fig. 26), and they differ from those of the Salani in that onion-skin weathering has not usually commenced to develop, and hence the boulders are angular. Mulifanua flows sometimes occupy valleys in pre-existing rocks (e.g., at Falefa, fig. 17).

Weathering is moderate only, and soil depths are of the order of 12 in. At Malie (northern Upolu, 5 miles west of Apia) drillholes showed an average of 8 ft of weathered rock and soil on top of hard rock.

Lithology

The rocks are grey and black, virtreous, porphyritic and non-porphyritic basalts, more or less vesicular and interbedded with aa. The prophyritic

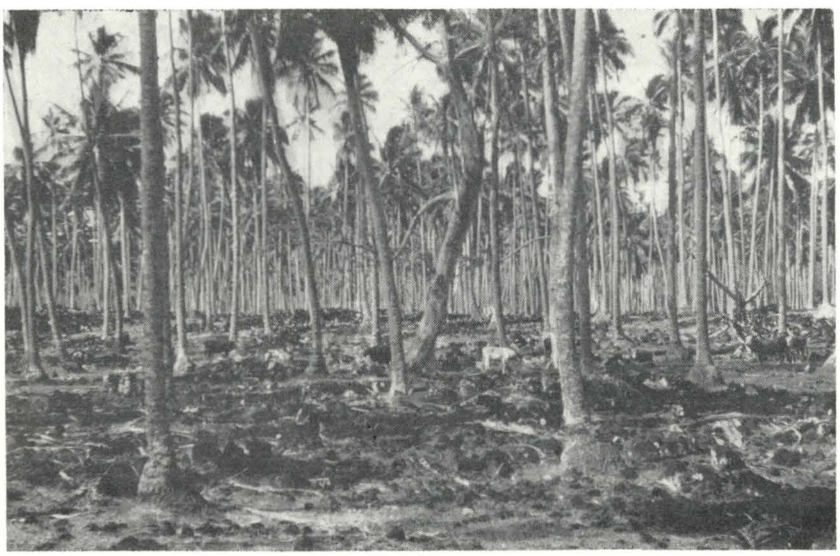

Fig. 26: Stony soil on Mulifanua Volcanics, New Zealand Reparation Estates Plantation, Mulifanua district, Upolu.

variety is the most common and contains phenocrysts of olivine 2–3 mm in diameter. The upper surfaces of the flows are characteristically ropy (pahoehoe), broken into hexagonal blocks, and cracked into 6–12 in. plates. Large, pale green olivine phenocrysts (like those of the Fagaloa) are uncommon in this formation, although some rocks are locally very rich in small feldspar phenocrysts.

Petrography (by R. N. Brothers)

There is a strong petrologic similarity between the rocks of Mulifanua formation and those already decribed from the Salani Volcanics. Not only are rock types exactly the same, but also the detailed petrographic descriptions of one formation are directly applicable to the other. In addition, the proportions of *olivine basalts* to *dolerites* to *analcite basalts* appear to be the same in both formations. This outstanding petrographic affinity supports the field evidence, which suggests that the Salani and Mulifanua Volcanics belong to periods of eruptive activity that have overlapped.

Relation to Older Rocks

The Mulifanua may be distinguished from the Salani Volcanics largely on their lesser erosion and weathering. The lack of deep watercourses and the angularity of surface boulders are the most important criteria.

As has been stated, in eastern Savai‘i the relation of the Mulifanua to the Salani appears to be that of younger flows filling the lagoonal area between an older flow coastline and an offshore reef. South of Sasina, in Savai‘i, Mulifanua lavas have filled a canyon previously cut in Salani rocks. In western Savai‘i, east of the intake for the Sala‘ilua water supply, Mulifanua rocks rests on a soil developed on a weathered basalt that is considered to be Salani.

Age

The lack of severe erosion of the Mulifanua rocks indicates their young age, the limits of which are given by the relationship of the volcanics to the coral reefs.

The reported occurrence of coral towards the bottom of the 130 ft Afia well (i.e., near sea level), indicates that there at least the Mulifanua basalts have buried a coral reef. A similar condition is indicated by the low-lying strip of Mulifanua basalts bordering Salani lava slopes along the east coast of Savai‘i. At the time of burial, the reef may have been at sea level, or it may have been abandoned by a falling sea level in the early stages of the Last Glaciation. There seems to be no evidence one way or the other, but it is obvious that sufficient time for reef formation intervened between eruption of the local Salani Volcanics (that are presumed to underlie the reef), and appearance there of the Mulifanua basalts. The Salani rocks beneath the buried reef must have been emplaced during or before the sea-level conditions leading to the formation of the reef (i.e., prior to the fall in sea level of the Last Glaciation).

The younger limit of the age of the Mulifanua Volcanics is given by the occurrence of the present wide barrier reefs offshore. If the barrier is assumed to have commenced as a fringing reef on a much lower part of the cone when sea level was lower than now, and to have grown vertically upwards as the sea level rose, the position of the initially low sea level can be calculated. Calculations of the depth at which the present reef would meet the continued slope of the basalt flows in the Mulifanua area range from 75 to 200 ft according to the assumptions made. This range is wide, but not inconsistent with the amount of the fall in sea level in the Last Glaciation (more than 190 ft in Auckland, Brothers, 1954, and possibly 270 ft as shown by the 45 fathom shelf) when the errors of calculation are considered. Now although the basalts at Mulifanua may not be the youngest of the group, they are evidently of an age approximating to the maximum of the Last Glaciation. To sum up briefly, the Mulifanua Volcanics probably span much of the time range of the Last Glaciation, and there is no evidence of their being outside that range.

Lefaga Volcanics

Name

Lefaga Bay is on the south coast of Upolu, 15 miles south-west of Apia, towards the western end of the island.

Distribution

The Lefaga rocks are well developed in the western third of Upolu. They extend along the south coast from Sataoa almost to the head of Lefaga Bay, and descend almost to the north coast near Sale‘imoa. This is their only major development, although they occur also as a single thin flow reaching the sea 2 miles east of the mouth of Fagataloa River, Upolu. The formation has not been recognised in Savai‘i, but some of the western "Mulifanua" rocks there are very scoriaceous, and might be close to Lefaga in age.

Surface Expression

The surface expression is similar to that of Mulifanua rocks except that aa at the ground surface is more common, the lavas appear to have flowed out into the lagoonal area, and the reef is relatively close inshore.

Onion-skin weathering occurs locally, due possibly to the high feldspar content.

Lithology

Lefaga rocks are dark-grey and black feldspathic porphyritic basalts with much greenish and red scoria in thick irregular beds, and with many bombs and lapilli. Flow surfaces at the coast are highly scoriaceous.

Petrography (by R. N. Brothers)

Only seven thin sections were available from the Lefaga Volcanics, representing picrite basalts and dolerites.

The *picrite basalts* have some features that may be interpreted as indicating the presence of an intratelluric crystal fraction which is magmatically older, or eruptively younger, than the comparable phenocrystic elements of the Fagaloa, Salani, and Mulifanua formations. The olivine phenocrysts are of two types: the first type is euhedral, although generally resorbed to some degree; the second type, fairly abundant, is anhedral with undulose translation lamellae and also is resorbed to a large extent. The latter type of phenocryst is regarded as originating at the base of a magma body where peridotitic clots have been formed by gravitational accumulation of olivine. The pyroxenes of these rocks appear to be titaniferous and are confined to the groundmass along with sub-equal quantities of iron ores. Brown basaltic glass forms occasional intersertal pockets. Plagioclase feldspars are accessory, and in 16638 the laths have been largely replaced by analcite.

The *dolerites* all contain phenocrystic olivine which has been strongly resorbed and carries heavy marginal zones of iddingsite; in 16607(2) coronas of pyroxene have been produced by reaction. Pyroxene crystals are titaniferous in 16607(1), and are subophitic to the labradorite feldspar, but the pyroxenes in 16607(2) and 16608 seem to be non-titaniferous and show strong zoning with an increase in iron content in the outer layers. The plagioclase of 16607(1) and 16608 shows minor core replacement by analcite, and small patches of K-oligoclase appear in the mesostasis of both rocks.

Relation to Older Rocks

The main lithological difference from Mulifanua rocks is the predominance of scoriaceous aa in the Lefaga Volcanics.

The Lefaga are presumed to be younger than the Mulifanua Volcanics since the width of the offshore reef is less. This may imply that the Lefaga basalt flowed into, and partially filled a pre-existing lagoon, or that the reef commenced to grow at a time of higher sea level, later in the Flandrian Transgression than the last extrusion of the Mulifanua rocks.

Age

The age is presumed to be early Holocene.

Puapua Volcanics

Name

Pu‘apu‘a is the northernmost village of Fa‘asaleleaga in eastern Savai‘i. The country to the northwest is covered by young basalt flows, the type Puapua Volcanics.

Distribution

The Puapua Volcanics contain all young, but not historic, volcanic rocks. In Upolu, the 10 square miles or so of O le Pupu in the centre of the south coast, some of the more recent cinder cones (e.g., Fito and Tafua upolu, fig. 27), and a few minor valley flows (at Lefaga, Lauli‘i, and Soaga Valley) are referred to this formation. Puapua rocks are more common in Savai‘i, where large eruptions from To‘iavea, Mafane, and other cones poured vast quantities of lava north-eastwards towards Pu‘apu‘a, and south-eastwards to the east and west of Palauli. Large flows, originating at or near the centre of the island, flowed past Letui in the north and to Gataivai and Taga in the south.

Surface Expression

The ropy lavas of the Puapua Volcanics have covered pre-existing flows, have filled gorges, and have flowed over high scarps (e.g., south-east of A‘opo) cut in pre-existing rocks.

They generally have a fairly low gradient, and a relatively even surface. Extensive swamps have developed in some low depressions (e.g., Vaiutumaga in east Savai‘i). Where, because of pre-existing topography, the gradient is steeper, the surface of the flow is extremely broken, and angular boulders cover the ground surface, e.g., near Siga Spring. Alias occur rarely, and water flows over Puapua rocks only where they form a thin skin on older rocks (e.g., Lata River at Sili).

Puapua cinder cones (e.g., Tafua upolu) are still fresh and perfectly preserved. Puapua rocks are but little weathered and soil is thin. Alluvial silt, however, covers them locally and even collects

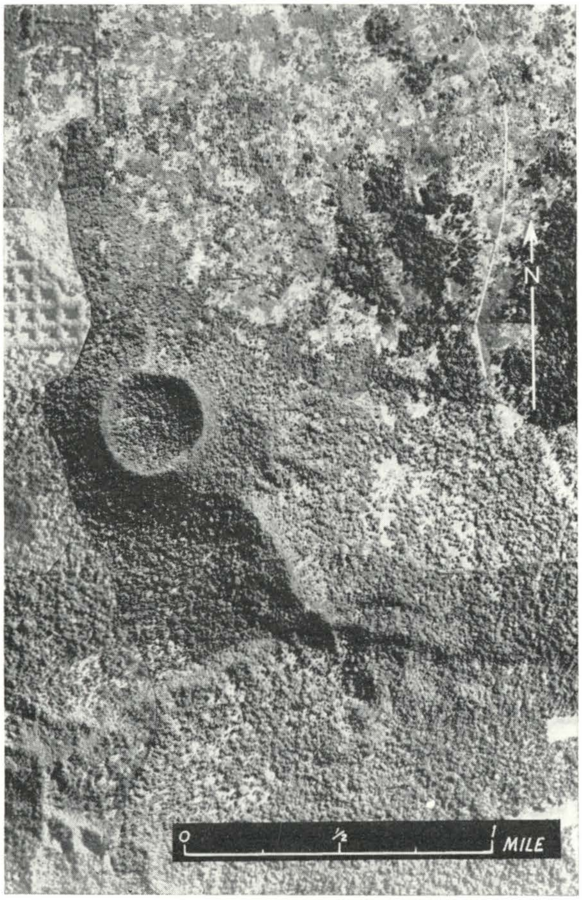

Fig. 27: Tafua upolu, a large Puapua cinder cone. The cone is situated on one of several partly buried ridges of Falagoa Volcanics the crests of which barely protrude above the surrounding Mulifanua lava slopes.

thickly in cavities (e.g., at Sili 15 in. of such "soil" has accumulated in horizontal cavities 2 ft down).

A reef is not developed offshore. Puapua basalts have in fact filled in the lagoonal area between pre-existing rocks and the reef (fig. 18). At the eastern end of O le Pupu in southern Upolu, solid coral shows below basalt at the coast. Having reached the reef, the lava must then have descended rapidly into deep water leaving a cliff at the old position of the reef. This has locally been cut into by the sea, and a 15 ft bench survives in the Gataivai area of south Savai'i (fig. 21). Puapua coastline generally is finely dentated, and may have a narrow wave-cut bench (fig. 18).

Lithology

Puapua lavas are dark grey to black pahoehoe basalts, slightly to moderately vesicular, containing phenocrysts of feldspar and pale green olivine. The cinder cones consist of black and red cinder, scoria, and scoriaceous basalt. Coral fragments were found in an ash bed within Puapua basalt at Gataivai (fig. 21).

Tafua savai'i is a Puapua cone that erupted much ash and tuff, as a result of the interaction of hot lava and sea water in the underlying porous Puapua basalt sheets.

Petrography (by R. N. Brothers)

Picrite basalts are represented by thin sections 16601(1) and 16642(2) in which phenocrystic olivine, and some peridotitic fragments, are seated in a groundmass consisting of intergranular pyroxene, iron ores, rare olivine, and zoned plagioclase laths with composition range An_{70} to An_{50}. Occasional small patches of basaltic glass appear in 16601(1). *Limburgitic basalt*, with a glassy, feldspar-poor groundmass, was collected near Alaoa power station.

Olivine basalts from three localities contain large crystals of olivine, which are partly resorbed, and labradorite feldspar. Pyroxenes are confined to the groundmass along with ilmenite and feldspar. 16643 is doleritic in texture, with vesicles filled by calcite and patches of potassium oligoclase throughout the mesostasis. The *vitrophyric basalt* of 16601(2) consists approximately of 60 per cent of basaltic glass in which are embedded phenocrysts of pyroxene, labradorite, and olivine, the latter showing no signs of resorption.

Vitric tuffs from the Puapua Volcanics show no sign of conversion to palagonite since the refractive index of the clear brown glass shards is always high. Crystal fragments of olivine and pyroxene are present in small quantities, but there is a notable absence of accidental rock fragments other than older (Vini) vitric tuffs.

Relation to Older Rocks

Puapua rocks differ from those of the Mulifanua and Lefaga Volcanics in that only the thinnest soil has developed on top of them. The lithology of their lavas is extremely constant. No reef is developed offshore.

Puapua basalts have partly buried a fault scarp in Mulifanua rocks on the northern side of the summit line in the western half of Savai'i, and in the extreme west of that island have buried sea cliffs cut in the Mulifanua rocks. In other parts of Savai'i, Puapua lavas have flowed down valleys cut in Salani rocks, and occasionally can be seen to overlie a weathered zone in the latter (e.g., Vanu River).

Age

Since Puapua basalts have no reef offshore, it is presumed that they are young. At Pu'apu'a itself they overlie coral beach sand (Tafagamanu Sand) at 5 ft above sea level. In New Zealand, low raised beaches exist on the Hauraki Plains and have been dated by radiocarbon methods as 2,270 years old (Fergusson and Rafter, 1957). Evidence of higher and older post-Glacial sea levels exists in New Zealand (15 ft terrace on West Coast, 4,600 years old, Fergusson and Rafter, 1955), and probably indicates the post-Glacial Thermal Maximum. The 15 ft bench at Gataivai was probably cut at the time of the Thermal Maximum (cf. the "6m" level at Tutuila – Daly, 1924, p. 124–5), and the formation there must consequently be slightly older. Hence the total age range of the rocks of the Puapua Volcanics would be from a little earlier than the post-Flandrian Thermal Maximum up to immediately prior to historical times (possibly 3,000 B.C. to A.D. 1,500). Tafua savai'i is presumed to be post-Thermal Maximum in age.

Aopo Volcanics

Name

A'opo is a village in north-central Savai'i that is surrounded by historical lava flows.

Distribution

Aopo rocks are restricted to Savai'i. In about 1760 lava from Mauga Afi flowed past the west side of A'opo to the sea, and covered large areas to the south-west, west, north-west, and north of the village (fig. 5). In 1902 relatively small eruptions occurred from fissures at Mauga Mu on the island summit to the south of A'opo (fig. 1).

Lava from the 1905–11 eruptions of Matavanu flowed north-eastwards to the sea at Mauga, and thence spread north and south in the lagoonal area.

Surface Expression

The rocks are extremely fresh and almost without soil, and in places (e.g., south-east of Fagamalo) are almost devoid of vegetation (fig. 28). Close to the edges of the flow, where soil underlies the flow at no great depth, however, trees have been able to root down to below the lava, and vegetation is thick. In the case of the 1760 flow, vegetation is scanty at low altitudes but above 1,000 ft becomes progressively heavier, so that on the crest of the island at 3,000 – 4,000 ft it can scarcely be distinguished from forest on older rocks. This is undoubtedly due to the

Fig. 28: Lava field (Aopo Volcanics) near Mauga, Savai'i. Showing typical pahoehoe basalts erupted from Matavanu (1905–11).

greater and more persistent rainfall at the high altitudes.

The surface of the flows is ribbed and puckered in very diverse ropy flow patterns (fig. 28), studded with knobs, blades, and spines, and covered with a brittle glassy skin of flattened bubbles and flakes that crackles as one walks on it. The lava flows are heaped up in waves and domes (tumuli) and broken into upturned or sunken slabs, with gaping chasms and downbreaks, all giving the impression of chaotic confusion.

Viewed from the air, Aopo coastlines appear smooth (as opposed to dentate in the older Puapua rocks) (fig. 19).

Lithology

The rocks consist of ropy, vesicular, porphyritic (feldspar and olivine) basalts, with but little aa. Such aa as was seen is blocky, loose, and appears to have been transported on the surface of the flows and to have accumulated along the margins.

Relation to Older Rocks

Aopo lavas lap over Puapua flows in the area around Mauga, and near A'opo. The sparseness of their vegetational cover, near these villages, contrasts sharply with the thick growth on Puapua flows; but a similar vegetational differentiation is impossible at higher altitudes.

These lavas, like the Puapua, flow over scarps in Mulifanua and Salani rocks.

Age

Aopo rocks are historical by definition. Their oldest date (A.D. 1760) was arrived at by reference to Samoan tradition (Thomson, 1921).

Marine Tuffs and Sedimentary Rocks

Vini Tuff

NAME

Vini is a common local name for Nu'utele Island, 1 mile south-east of Cape Tapaga at the south-eastern extremity of Upolu.

DISTRIBUTION

Vini Tuff forms virtually the whole of the islands of Apolima (between Upolu and Savai'i – fig. 29), Fanuatapu, Namu'a, Nu'utele (Vini), and Nu'ulua (all off the eastern coast of Upolu), and of Cape Tapaga (south-east Upolu) (fig. 4). It occurs up to 475 ft above present sea level on Apolima (fig. 29).

SURFACE EXPRESSION

All exposures of this formation are of marine tuff rings in various stages of erosional destruction. Apolima is the most perfect, with only one breach through the ring, and Cape Tapaga is probably the least, where only one small segment of the original cone remains. In general the individual beds of the tuff dip radially outwards, presumably away from the centre of eruption, at angles of up to 30°. Apolima is outside the reef area, the reef off Aleipata has grown out to Fanuatapu and Namu'a, and Nu'utele and Nu'ulua have small reefs separate from that surrounding Upolu.

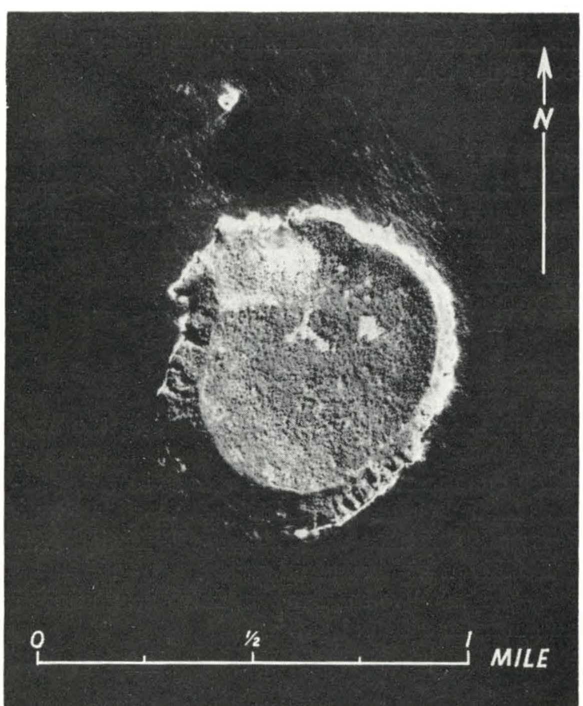

Fig. 29: Apolima Island, an eroded cone of Vini Tuff. The cliffs are some 200 ft high, and the crater wall is breached on the north side. Apolima village lies near the breach.

LITHOLOGY

The Vini Tuff consists of hard, thick-bedded, calcareous tuff, over 475 ft thick. Mollusc shells have been found within it up to 30 ft above sea level, and coral fragments are common up to that level. Small coral fragments have been noted less frequently up to 200 ft on Apolima, and may occur higher. The lower beds are well bedded, and in places finely laminated (especially on Nu'utele), but only faint massive bedding was seen in rocks higher than 30 ft above sea level. Basalt fragments (up to 3 in. across) tend to be more common nearer to sea level than higher up. At Cape Tapaga a 6 in. bed of cemented coral sand dipping 10°E is interbedded with normal tuff about 20 ft above sea level.

PETROGRAPHY (by R. N. Brothers)

Vitric tuffs with abundant glass shards enclosing ferromagnesian minerals are abundant in this group. In 16620 the glass appears partially devitrified, but in all other thin sections its fresh appearance and high index of refraction indicate unaltered basaltic glass rather than the palagonite suggested by Thomson (1921). Crystal fragments of olivine and pyroxene, together with chips of olivine basalt, dolerite, and older pyroclastic ejecta, are welded by the glass into a compact rock. Secondary calcite is abundant in patches throughout the fragmental glass mesostasis, e.g., 16656(1), and as a replacement product in the larger ferromagnesian grains. A zeolite mineral, tentatively identified as heulandite, occurs in thin seams throughout the tuffs, along the boundaries of calcite patches, and as vesicle fillings, e.g., 16658(1).

PALEONTOLOGY

Dr C. A. Fleming has identified the following fossils from fragmentary material: Cape Tapaga – indet. corals; Fanuatapu – *Conus* (s. lat.) sp., and nodular coralline material; Apolima – *Cypraea* (s. lat.) sp., and *Pyrene* sp. indet.

RELATION TO OLDER ROCKS

The Vini Tuff is of a unique lithology, so that there is no likelihood of its being confused with other formations. Its most important features for differentiation are its tuffaceous and calcareous composition, and the tuff-ring forms.

Nowhere is the Vini Tuff seen in contact with rocks of any other formation, and its relation to the Fagaloa rocks especially, is unknown. The degree of erosion of the Fagaloa Volcanics is so much greater than that of the Vini Tuff at Apolima that the former would be considered the older on that basis. The relation of the tuffs of Cape Tapaga to the nearby Salani Volcanics suggests that the former are the older, especially in that they are not underlain by Salani rocks and that the latter show no features of high sea level.

AGE

The age of the Vini Tuff is known only within wide limits. The rocks are presumably much less resistant to erosion than the Fagaloa Volcanics, on comparison with which the tuff rings would appear to be considerably younger. A difficulty arises here in that while the tuffs of the eastern islands have a wide reef adjoining, those of Apolima Island (fig. 29) have no reef, implying considerable age differences. The lack of reef led Stearns, who saw the island only from the air, to suggest that it is Recent in age (1944, p. 1324). However, the presence of molluscs, coral fragments, and fine bedding up to 30 ft above sea level in all the tuff islands indicates contemporaneity during a 30 ft-high sea level and is good evidence for sound correlation, regardless of considerations of present coral reefs.

The Vini Tuff pre-dates the Salani Volcanics at Aleipata (see above), and the lull in volcanism between the Fagaloa and Salani makes it possible that the Vini Tuff represents an early stage of Salani volcanism. The tuff was deposited during a sea-level stand at about 30 ft above present level (possibly Last Interglacial).

The Vini Tuff is thus tentatively regarded as a marine correlative of early Salani rocks, of Last Interglacial age.

Lalomauga Alluvium

Lalomauga is a village in Upolu, 15 miles east of Apia and 3 miles inland. A nearby tributary to Falefa Stream was filled with alluvium after its outlet had been blocked by a Mulifanua lava flow down the main valley (fig. 16 and 17). This Lalomauga Alluvium is now preserved in terraces up to 30 ft above stream level (fig. 6) and is locally bouldery. Similar deposits, of too small an area to map, may well occur elsewhere in Samoa.

Clearly this formation is intermediate in age between the Mulifanua flow and the younger alluvium that exists at a lower level in nearby valleys. It may be in part contemporaneous with the Puapua Volcanics.

Nu'utele Sand

Nu'utele is the formal name for the island, locally known as Vini Island, off the south-eastern corner of Upolu. Raised beaches there stand at 15–20 ft above sea level. They are formed of coral sand, and are the type of the Nu'utele Sand. This formation also extends inland from the landing place on Apolima Island (fig. 29). There, 4 ft of coral sand and gravel rest upon weathered Vini Tuff, 8 ft above sea level at the coast. The terrace rises slightly inland, and probably represents a sea level about 15 ft higher than the present.

The Nu'utele Sand was deposited presumably at the same time as the 10–15 ft bench was cut in Puapua rocks at Gataivai (fig. 21), and a deposit of rounded gravel with coral resting on that bench is correlated with the Nu'utele Sand. At its inland margin the gravel is 15 ft above sea level. Since younger Puapua rocks are known, the Nu'utele Sand is contemporaneous with part of the Puapua Volcanics, and in particular with that part thought to be about 4,600 years old (see p. 31).

Tafagamanu Sand

Tafagamanu is a village in Lefaga Bay (south-west Upolu), 15 miles south-west of Apia. Raised coral sand, resting upon basalt, is common in this area. At one section 18 in. of coral sand over-lies 9 in. of soil and boulders in a low cliff, the top of which is 5 ft above sea level.

The Tafagamanu Sand is common around the coast of Western Samoa. Very many villages are built upon it at the convenient height of about 5 ft or slightly more above sea level. Some of these deposits are raised beaches, others are raised beach ridges, but the coral sand is similar throughout. Locally, coral, or even basalt gravel, is interbedded with the sand. A sample of sand was collected for radiocarbon dating, and may be about 2,300 years old (see p. 30).

Evidence of sea-level stands at 5–6 ft above the present is known from elsewhere in the Pacific (e.g., Tahiti, Williams, 1933, p. 23).

Late Terrestrial Deposits

Apart from the Lalomauga Alluvium, appreciable areas of alluvium are confined to the mouths of the larger streams and rivers. The gravel of the present bed of the Vailoa River (south Upolu) has been cemented (along with land-snail shells) by iron oxide. Relatively thin, bouldery sheet-flood alluvium is common on much of the country underlain by gently sloping basalt flows (e.g., at Palauli in Savai'i). One large area of thick bouldery alluvium is present near Apia.

Swamps are relatively common, tending to form in the minor irregularities of areas covered by flat basalt sheets, in the higher country where drainage has been impeded by young flows, in some of the older volcanic craters, and behind beach-sand ridges.

Talus deposits have been mapped at the base of many steep Fagaloa slopes.

Late Marine Deposits

A growing coral reef exists off much of the Samoan coastline, the presence or absence, and distance offshore, depending upon the age of the coastal rocks (fig. 17). Raised reefs are unknown as yet on land, probably because any that might be present have been covered by younger basaltic material. A coral reef shows below Puapua basalt at the eastern end of the O le Pupu, but is below low-water mark. Coral was reputedly found towards the bottom of the 130 ft well at Afia (i.e., close to the sea level). This well, in the Mulifanua area of Upolu, commenced in Mulifanua rock.

A few large white calcareous boulders, well covered by mosses and lichens, lie in the stream and on the banks near Fale o le Fe'e (in the hills south of Apia), at 1,000 ft or so above sea level. Mr M. G. Irvin of Henderson, New Zealand (pers. comm.), saw a block 4 ft × 4 ft × 5 ft there in 1954, although nothing so big was seen in 1956. It cannot be proven easily that these blocks were not derived from the nearby Fagaloa or Salani rocks, but it is presumed that they were carried there by the Samoans for building purposes at Fale o le Fe'e.

Present-day beaches are commonly of coral sand, with rarer stretches of coral or basalt gravel. Locally, these beach deposits become cemented by calcite (e.g., Fa'asaleleaga – sand; west Savai'i – gravel. See also Daly, 1924, pp. 135–40). As noted by Thomson (1921, pp. 64–5, fig. 2), the resulting cemented beds dip seawards at about the same angle as the beach itself.

CHAPTER 4—STRUCTURE AND GEOLOGICAL HISTORY

Introduction

The Samoan archipelago is one of a number of such groups lying eastwards of the region of island arcs that borders the south-west Pacific Ocean.

The relation of the volcanic oceanic islands to the arcuate islands and the nature of the crustal structures beneath them have attracted geological thought for many decades since Suess (1908–09) first developed, in 1888, the concept of arcuate mountains and island arcs. The earlier observers (Dana, 1890; Gregory, 1908) indicated the various island groups and lineaments but often were not able to differentiate the types of structures concerned. Later workers developed a number of different hypotheses, and contributed a bulky literature on the structural problems. It is not the purpose of this account to discuss these hypotheses or to review the literature: an excellent discussion of the problems and a useful summary with paleogeographic emphasis is given by Benson (1923, pp. 1–10).

The distribution of the volcanic rocks and of ocean deeps was discussed by Marshall (1912, p. 28) and the differences of structures in the island arcs and chains were shown to be of fundamental importance. Marshall showed that entirely different island structures and rocks lie on opposite sides of a boundary that follows the Tonga-Kermadec Trench from New Zealand and swings west around Fiji past the New Hebrides and Solomon Islands (fig. 35). West of the boundary lie island-arc structures, with fold mountains and plutonic intrusions typical of continental margins. Close to the boundary, island arcs are fronted by deep trenches (fore-deeps), volcanoes occasionally erupt,* and fold movements are still occurring along associated seismically active belts.

East of the boundary the islands are scattered in a more random fashion in broad linear chains, very little evidence of fold movements is known (cf. Marshall, 1912, p.32), and no continental rocks occur in place (Marshall, 1924, p. 733). Seismic activity is associated only with volcanicity, the products of which arise from a parent alkaline basaltic magma. Marshall did not specifically name this boundary but termed it the andesitic line, and suggested that it corresponds to the margin of the Pacific basin. Born (1933) drew a boundary closely parallel but east of that of Marshall, and named it the Andesite Line. Macpherson (1946) named the former boundary Marshall's Line, Stearns (1946) termed it the Sial Line, and both considered it to be the north-east boundary of the Australasian continent. A more generalised distinction between the island groups of the south-west Pacific was made by Hobbs (1945), into regions of strewn islands, regions of arcuate and strewn islands, and regions of arcuate islands. These distinctions were followed by Hess and Maxwell (1953), and elaborated by Gutenberg and Richter (1955). Samoa is classified in the group of arcuate and strewn islands, lying north-east of the Marshall or Andesite Line.

* An eruption at Fanua Lai, Tonga Group, was recently reported (New Zealand Press Association, Suva, 20 June 1957).

Samoan Structure

The Samoan islands are situated in a unique position, directly in line with, but striking at right angles to, the main reach of the Tonga Trench, and on the opposite side of that trench to the Andesite Line.

Density of Volcanic Eruptions in Space and Time

A great number of volcanic vents are exposed on the present land surface – probably 500 in Savai'i alone – and many more may be presumed to lie buried. Several vents, however, were probably formed during many "single" eruptions (see fig. 1, for example, showing the number of vents involved in the 1902 eruption of Mauga Mu). It is thus impossible to assess accurately the number of individual eruptions that are indicated by the present land surface, but the number must be of the order of 200 (50 in Upolu and 150 in Savai'i). This gives an approximate density of volcanic centres (mostly shown by individual or multiple cones) of one per 9 square miles for Upolu and one per 5 square miles for Savai'i.

Such a density is far more comparable to that of the younger basalts of Auckland, New Zealand, where over 60 centres occur within about 250 square miles, than to that of the Hawaiian Islands, where volcanoes are spaced about 25 miles apart (Powers, 1917, p. 506). The proximity of Samoa to the Andesite Line may well be related to this fact.

Several assumptions are required to assess the density of eruptions in time. The oldest cones are of Salani age, and are thus presumably no older than the Penultimate Glaciation. Hough (1953) gave dates for the earliest phase of the Wisconsin (Last) Glaciation as 64,000 years B.P., and for the middle stage of the Illinoian (Penultimate) Glaciation as 310,000 years B.P., basing them upon uranium, ionium, and radium datings for Pacific Ocean core samples. The earliest Salani cones probably date from some time between these two figures. A low value of 100,000 years will be accepted for the purposes of the present calculation of eruption frequency, since the Salani might be restricted solely to the Last Glaciation (p. 41), and since the number of eruptions must be underestimated owing to the burial of some cones. Then, using the approximate figure of 200 volcanic centres, an average rate of one eruption per 500 years is obtained.

The total number of post-Mulifanua cones, erupted say in the post-Glacial period (for which time a length of about 10,000 years is generally accepted), is about 30 – roughly one eruption per 300 years. Three eruptions are known in the period A.D. 1760 – 1957. Although all these figures are clearly liable to large errors, it seems reasonable to infer that the recent rate of volcanism is not slower than the past average.

Volcanic Alignments

The Samoan archipelago trends generally east-south-east, with a few variations in the major trends of the individual islands (fig. 30).

In the eastern islands of Tau, Olosega, and Ofu, the most conspicuous alignment of cinder cones (representing the strike of the rift zone from which the lavas emerged and over which the cinder cones formed) is 110°. In Tutuila, two, possibly three, parallel rifts trend 070° (Stearns, 1944). The dominant alignment of cinder cones in Upolu is parallel to the length of the island – 110°. Alignments of cinder cones are not as lengthy nor as distinct in Savai'i; those in the western half of the island trend 110°, on the central uplands swing to about 090°, and, from the central uplands, two chains trend 110° and 140° to Tuasivi and Tafua savai'i respectively (fig. 30).

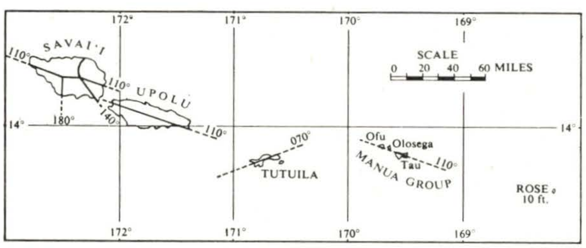

Fig. 30: Major volcanic alignments in the Samoan Archipelago (those of Tutuila and the Manua Group from Stearns, 1944).

Smaller, vaguely defined groups trend almost due south from the central uplands, and curve northward from the main group near To'iavea. Two fissures with small cinder cones on them strike 130° and 160° immediately east of Mauga Silisili (fig. 31).

Faults

The faults may be divided into two categories: large normal faults associated with landsliding or subsidence on a vast scale; and short small faults parallel to lines of cones in Savai'i, and occurring in Fagaloa rocks in Upolu.

Many of the short faults in Fagaloa rocks are apparent only as lines on air photographs, and no information could be gained as to whether they are reverse, normal, or transcurrent. Some of the lines may be only erosion traces of faults, or even strong dykes in the Fagaloa Volcanics. The faults strike in two well defined directions, north-north-east and east-south-east parallel to the main axis of the island.

Many of the small faults in Savai'i are also apparent only as lines or shadows in air photographs, but all strike parallel to the cone alignments and have cinder cones along them. In western Savai'i, near the cones Pulea and Anaota, two faults were seen to be downthrown to the south. It was not possible to ascertain whether they or any others are normal, reverse, or transcurrent. These small faults are the rifts or fissures from which the lava flows emerged, and are obviously of very similar age to the associated lavas and cinder cones.

The only large normal fault, the nature of which is reasonably certain, is that striking along the north side of the crest of Savai'i, and extending 15 miles from Sataua in the north-west to a point south of Sasina. The fault scarp is about 100 ft high close to sea level in the north-west, and increases in height to 500 ft at an altitude of 3,350 ft south of A'opo (fig. 1B), and is still higher a mile or so to the east. The west end of the scarp continues into the coastal cliffs beyond Sataua, and the east continuation is obscured by Mulifanua and Aopo Volcanics. Two west-facing scarps, 15 ft and 75 ft high, striking a little west of south from Safune Bay, are believed to

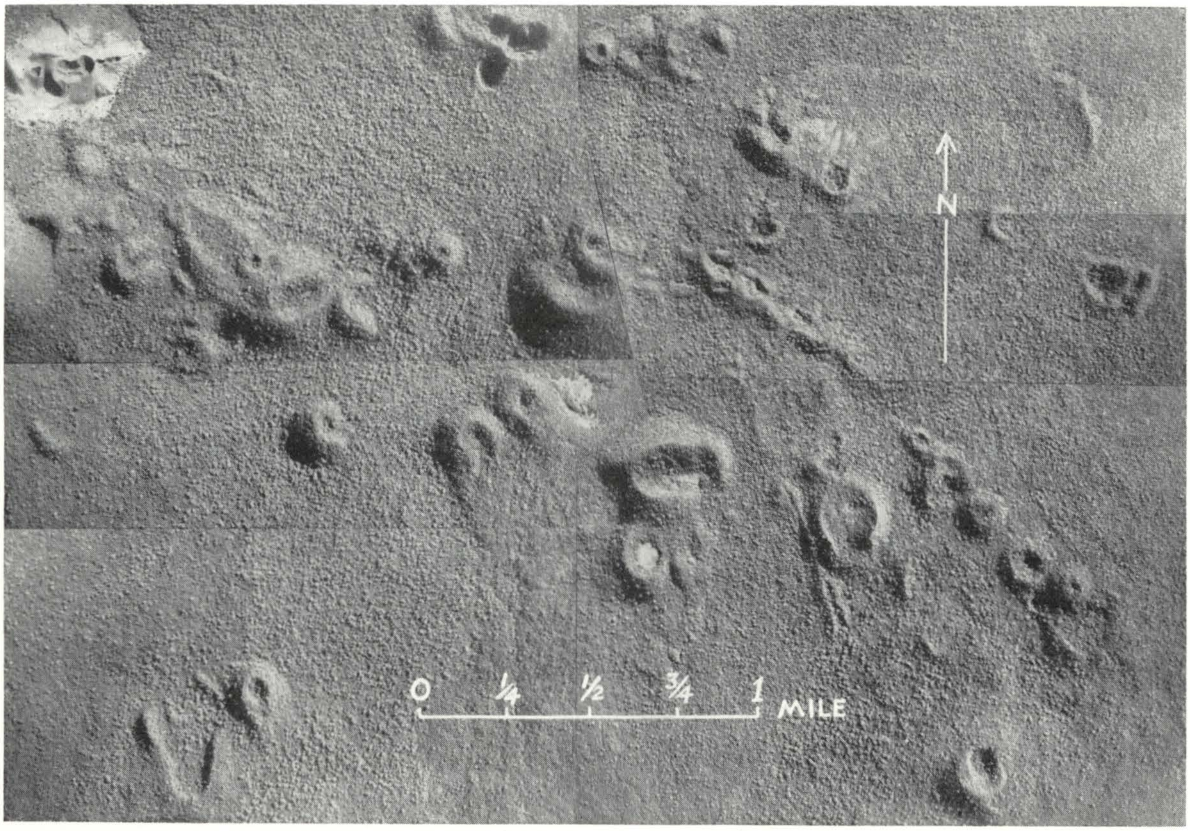

Fig. 31: Uplands of central Savai'i around Mauga Silisili (6,095 ft). Two fissures (right) strike 130° and 160°, fissure beneath Mauga Mu (upper left) strikes 090°. The lava plain is about 5,000 ft above sea level.

be associated with the fault; the eastern one near Safotu is possibly a further continuation of the main one.

The main fault displaces Mulifanua and Salani Volcanics, and is partly buried by Puapua and Aopo lava flows. It has been trenched south of Sasina by an amphitheatre-headed canyon, the floor of which is veneered with Mulifanua lavas and small Puapua cinder cones (fig. 13). Nearby, traces of one or two almost completely filled canyons are barely visible.

The fault movement is thus older than the Puapua lavas, younger than the Salani, and younger than many of the Mulifanua lavas. The only Mulifanua lavas that have flowed across the fault are those in the canyons south of Sasina, and others, with cones that blanket the fault scarp, at a point 6 miles south-east of Asau.

The normal nature of the fault is indicated by the way that the fresh, well preserved scarp dips (at about 50°) towards the downthrow (north) side. No indications of transcurrent movement were seen. The subsidence of the downthrow side is believed to be due to vast landsliding involving a large segment of the volcanic pile similar to that described by Fairbridge (1950). The best evidence for this is in the broad curvature of the fault-trace from 120° in the west, to 090° in the centre and 075° in the east, to possibly 015° to the north-east near Safotu. It is extremely unlikely that a curved fault such as this has resulted from the usual crustal stresses associated with a volcanic rift zone. It will be noticed on the map that several Mulifanua cones occur along the fault south and south-east of Asau, and that Mulifanua and younger cones (possibly including Matavanu) occur along probable fault branches to the east. Evidently the fault zone has functioned as a volcanic conduit and is probably intersected at depth by feeding dykes. This illustrates one possible contributing process by which an island with a simple volcanic alignment along a single fracture (almost like Upolu) could pass into a more complexly shaped island with several directions of volcanic alignments (e.g., Savai'i).

The way in which the major fault scarp merges into the coastal cliffs at Sataua, and indicates their fault origin, suggests that similar cliffs elsewhere, for which a fault origin is suspected, may be the result of huge subsidences caused by instability in the submarine levels of the volcanic edifice. Such cliffs (south-east Upolu, fig. 32, and south-west Savai'i),

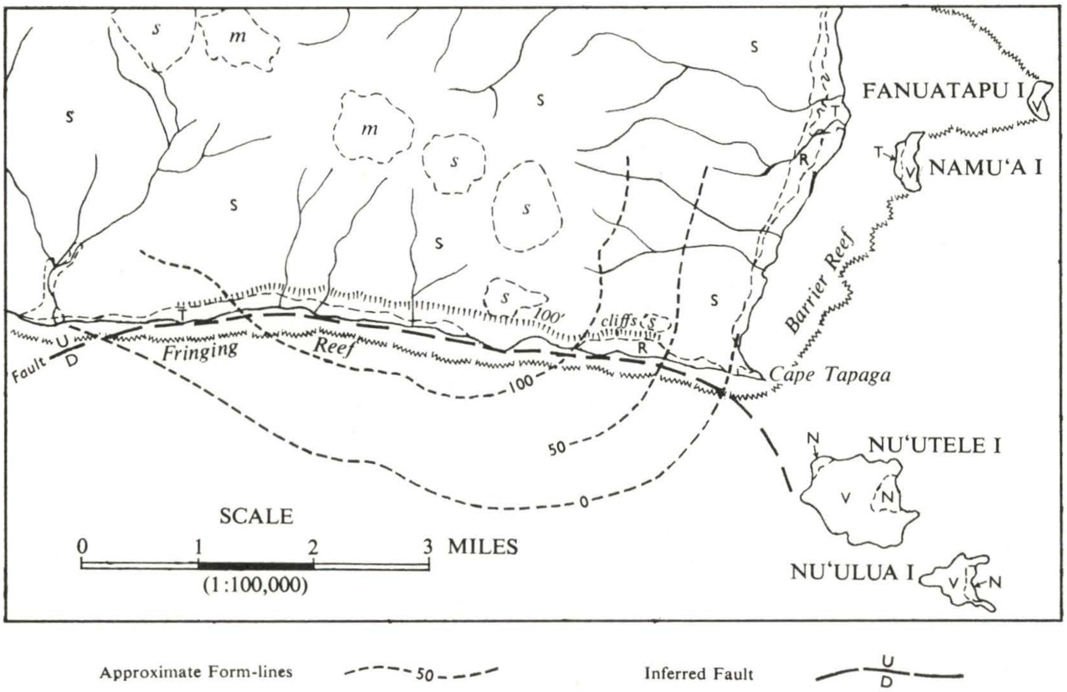

Fig. 32: Sketch map of south-east Upolu Island (for symbols refer to geological map). Showing reef off normal Salani coast (right) and off cliffed coast, approximate form lines and former extent of lava slopes, and inferred fault.

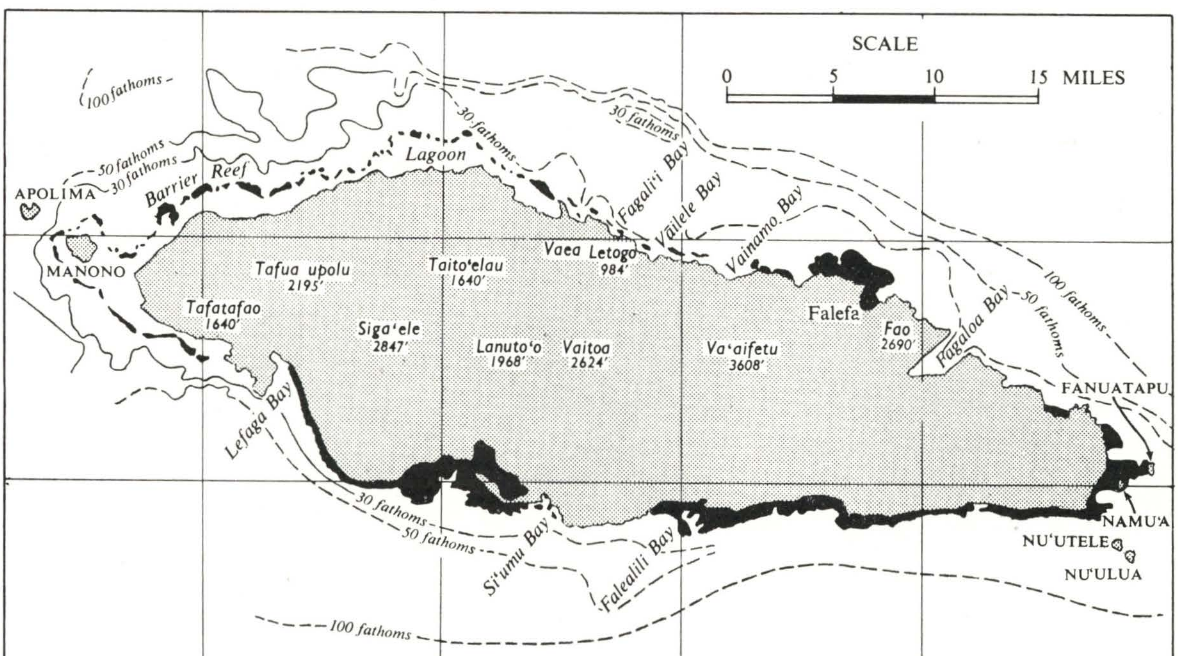

Fig. 33: Generalised bathymetry around Upolu Island (after Stearns, 1944, p. 1322). Coral reefs shown in solid black.

have been previously described (p. 28), and only their age need be considered. According to Stearns (1944, p. 1320) scattered soundings show that a submarine shelf less than 100 fathoms deep completely surrounds Savai'i island, and a similar shelf (or shelves) lies off southern and south-east Upolu (fig. 33). The deepest submarine shelves were formed when the sea stood at lower levels during the early Pleistocene; shallower shelves were formed by later Pleistocene low sea levels.

No subsidence is apparent of the shelf areas opposite the above-mentioned cliffed coasts, and it seems that the subsidence and initial formation of the cliffs must pre-date or be contemporaneous with the last Pleistocene low sea level (Last Glaciation) as was suggested by Fairbridge (1950, p. 85). The cliffs in Upolu are at least post-Salani, those in south-west Savai'i are in Mulifanua rocks, but near Falelima are partly buried by later Mulifanua lavas.

It thus seems that the normal faults associated with subsidence or landsliding, may be all approximately contemporaneous and within the time range of Mulifanua volcanism. It is tentatively suggested that the subsidence was caused by changing hydraulic conditions in the volcanic pile during the low sea level of the Last Glaciation.

Island Structures

The general structure of Western Samoa is that of an old volcanic terrain (Fagaloa), deeply weathered and eroded so that little or none of the original form remains, with a thick series of younger lava flows and cones rising over and largely burying the older rocks. Meagre evidence suggests that the rift zone whence came the Fagaloa Volcanics was parallelled by, or was possibly the same as, that from which the Salani and younger lavas were erupted.

The younger lavas are everywhere separated from the older by a strong erosional unconformity marked by a 6 ft to 10 ft weathering zone, the upper 2 ft of which is a deep red or purple clay soil (fig. 25). Younger lavas, occupying valleys cut in the older, have partly inverted the topography, and in general considerably reduced the earlier ruggedness of the uplands.

The dominant structures of the younger volcanic formation are those of the broad coalescing lava cones, and these arch over, and on the flanks dip away from, the main alignments of the cinder and ash cones. The cone alignments are described on page 50. In Upolu the cones are aligned in one direction along a definite crest some 2,000 ft to 3,000 ft high. The crest of Savai'i is much broader and higher (5,000 ft to 5,500 ft), and possibly because of the much greater thickness of underlying volcanics the cones are distributed only in short sub-parallel chains.

The lavas on the uplands are usually almost flat-lying, but the dips increase to about 15° around the flanks in western Upolu and north of the crest of Savai'i. In south Upolu the flank flows dip as much as 18° and in south-west Savai'i dips are 20° or higher. The latter dips are steeper than usual for Mulifanua Volcanics and suggest that the lavas flowed directly into the deep ocean not far from shore, and did not build up on a wide submarine shelf as did similar lavas elsewhere. The steep submarine slope south-west of Apolima Strait, if continued to the north-west, must lie very close to the southern coast of Savai'i, and may be the edge of a profound ocean deep. The approximate alignment of the submarine slope with the subsidence-fault cliffs of south-west Savai'i (see p. 28) and the presence on the slope of an analagous fault-line cliff (p. 32), suggests that the major subsidences are partly due to the steep angle of the submarine flank of the volcanic pile.

South-west Pacific Structure

The position of Samoa in the structural pattern of the south-west Pacific is sufficiently unique to warrant a brief consideration. The general bathymetry of the south-west Pacific is shown in fig. 34; the region of arcuate and strewn islands spreads across the centre of the area, trends north-east beyond the Fiji group, then swings sharply southwards past the Tonga and Kermadec groups. To the east it is bordered by the narrow Tonga-Kermadec Trench (shown in solid black). Smaller trenches occur on the south-west sides of the other island arcs. An excellent description of the Tonga Trench and adjoining features is given by Raitt, Fisher, and Mason (1955).

The trenches, the adjoining island arcs, and volcanic ridges are caused by crustal stress (fig. 35), which in the past was generally believed to be acting in directions at right angles to the arc structures. A discussion of the hypothesis of crustal mechanisms involved is given by Umbgrove (1947, Chapter 7). In the case of the Tonga-Kermadec Trench, there are as yet barely sufficient data to reveal the nature and direction of the crustal stress involved. Two lines of study that yield some indications are the directions of transcurrent faulting in New Zealand and seismic evidence from south-west Pacific earthquakes.

Wellman (1953, 1955) has demonstrated considerable transcurrent movements along a great number of faults, notably the Alpine Fault, in the

South Island, New Zealand. The zone of recent faulting and seismic activity strikes north-east through the centre of the North Island to the Bay of Plenty, wherein lies the small parallel White Island Trench described by Fleming (1952).

The New Zealand – Tonga features are almost parallel to the direction of clockwise (dextral) transcurrent faulting in New Zealand, which strongly suggests that they are associated with transcurrent faulting. Had the stress system that gives rise to this inferred transcurrent faulting been simple, and consisted of an easterly principal horizontal stress, the alignment of the Samoan islands, at right angles to the Tonga Trench, would, according to the analytical method of Anderson (1953), and the stress system described by Wellman (1954), be in the direction of normal faulting having an anti-clockwise transcurrent component. The very long straight lines of the oceanic volcanic islands are, in the opinions of Betz and Hess (1942) and others, the results of transcurrent faulting within the Pacific basin. While this may also be true of Samoa, the meagre seismic evidence from about the north end of the Tonga Trench suggests that there the direction of principal horizontal stress is swinging at right angles to the archipelago and the major alignment may not be entirely due to transcurrent faulting.

According to Hess and Maxwell (1953) a "strike-slip fault zone" may extend from the south end of the New Hebrides to the north end of the Tonga Trench (fig. 35); the authors presented little evidence

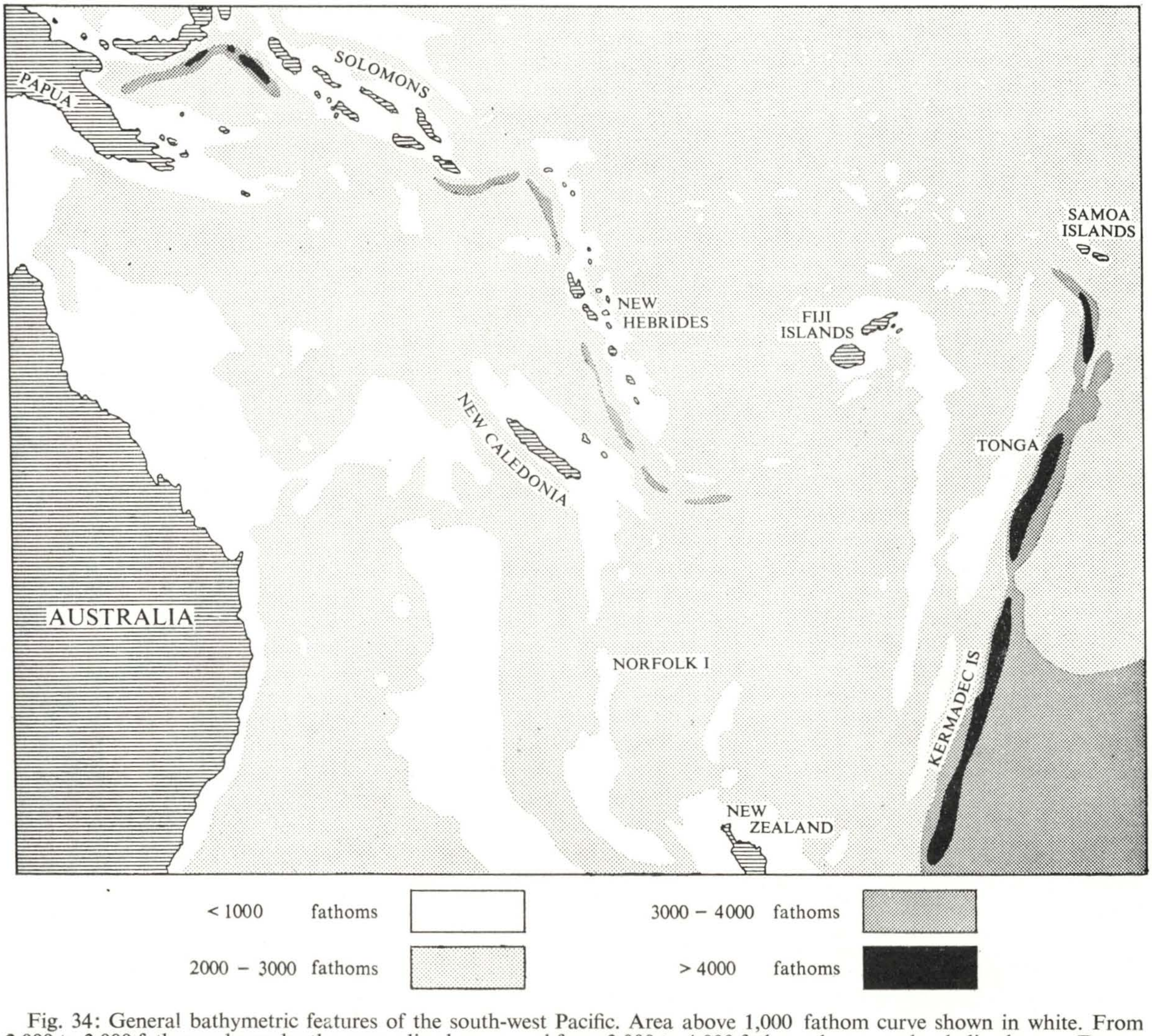

Fig. 34: General bathymetric features of the south-west Pacific. Area above 1,000 fathom curve shown in white. From 2,000 to 3,000 fathoms shown by the coarse lined areas, and from 3,000 to 4,000 fathoms by more closely lined areas. Deeper than 4,000 fathoms is solid black. Trenches along convex side of arcs are well shown, as are the ridges shallower than 1,000 fathoms (after Hess and Maxwell, 1953).

for it, and no relevant information was obtained in the present work.

Eiby's work (1955) on the initial movements on seismograms in New Zealand indicates that most of the recent local earthquake shocks that originated at north-east-trending faults did so by a clockwise fault movement. A wider application of the method of Byerly (1938) to the Pacific basin has been attempted by Hodgson and Milne (1951), and by Hodgson (1955), who concluded (p. 207) that in the south-west Pacific the faulting is predominantly transcurrent. From the initial movements of the major earthquakes ("First Arrivals"), Hodgson determined the attitude and direction of movement on two possible fault planes along which the movement may have occurred. From these the probable direction of the principal horizontal stress in the crust may be inferred (Lensen, 1958). The results available from Hodgson's study are shown in fig. 36. The indications of direction of principal horizontal stress are extremely meagre. They suggest, however, that the direction along the Tonga-Kermadec features is similar to that in New Zealand, but that at the northern end of the Tonga Trench the direction swings northward. It may be highly significant that the change in direction occurs where the trench swings westward.

On the present evidence there is no conclusive way of incorporating the meagre evidence from Samoa, and the precise implications of the volcanic

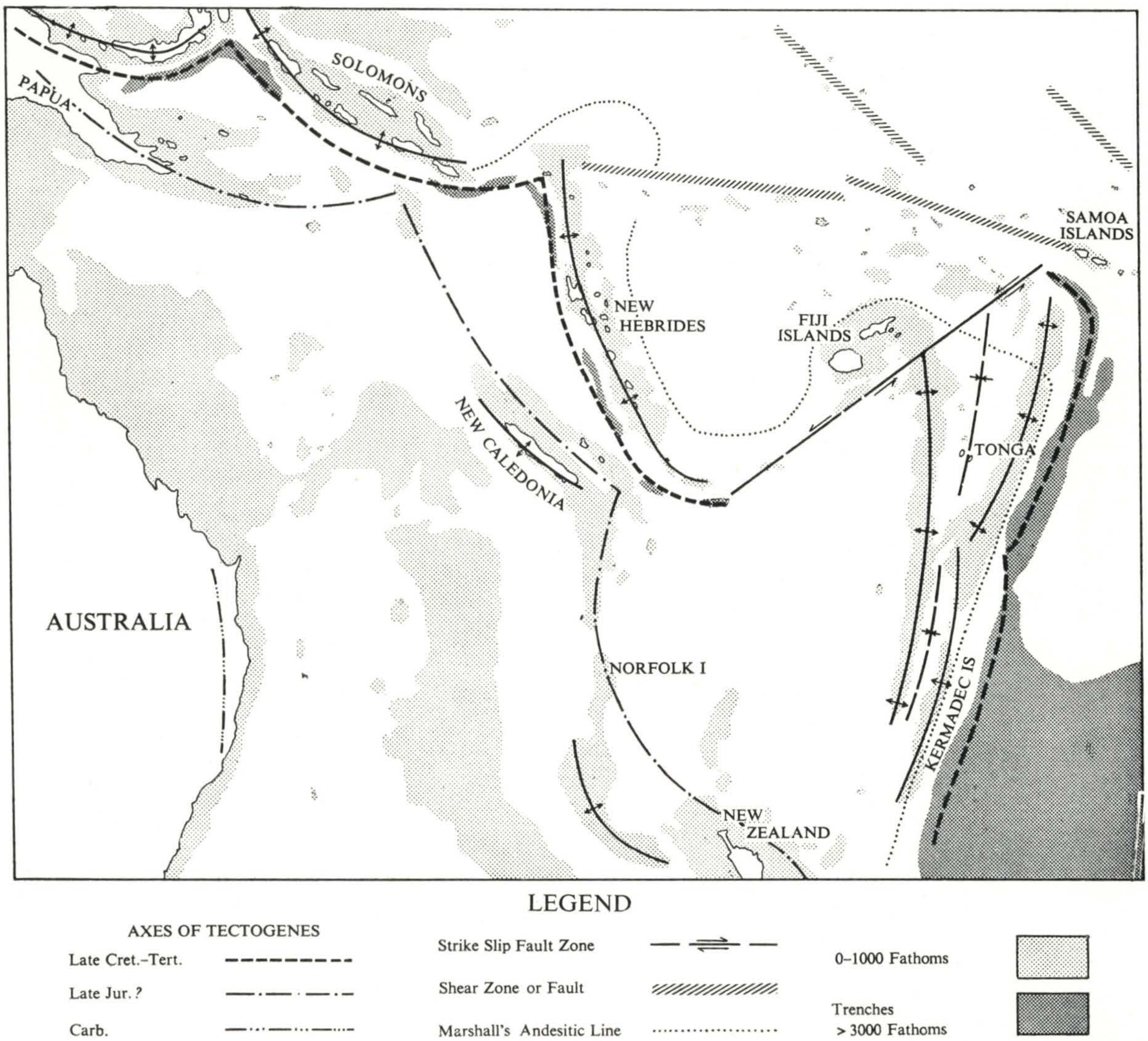

Fig. 35: Structural interpretation of bathymetric features. Heavy black-dashed lines represent postulated axis of tectogene where the crust has buckled. Positions and ages of older tectogenes are estimated. Note postulated strike-slip fault zone extending from the south end of the New Hebrides to north end of the Tongas (after Hess and Maxwell, 1953).

alignments there (fig. 30) remain unknown. However, there is little doubt that the dominant alignment is 110°. The nearest known direction of principal horizontal stress (fig. 36) is east. This would be consistent with the alignment of 110° being due to normal-anticlockwise transcurrent faulting, and with the Tutuila alignment of 070° being due to normal-clockwise transcurrent faulting, as there is an angle of only 20° between the direction of principal horizontal stress and of transcurrent faulting.

In contrast to this hypothesis of transcurrent faulting, in which horizontal stress at an oblique angle to the transcurrent faults plays an important part, an alternative hypothesis, which is receiving increasing attention (e.g., Cotton, 1956, p. 191), ascribes major transcurrent movement to deep-seated drift (the cause of which is as yet unexplained) along the boundary ("geosuture") between a pair of the units of a primitive world-wide pattern of large irregular-polygonal compartments ("groundblocks") that extend into a deep subcrustal zone (Cloos, 1948). According to this hypothesis, if the New Zealand – Tonga features are attributable to the same groundblock drift as is believed to give rise to the clockwise transcurrent faulting in New Zealand, the major 110° rift of the Samoan archipelago would be related to clockwise transcurrent faulting.

The two hypotheses, based on principal horizontal stress, and groundblock drift, thus indicate opposite directions of transcurrent faulting beneath the Samoan islands. Unfortunately, there is at present insufficient evidence from Samoa to determine the directions of major movements.

Gravity Anomalies

As may be expected, the great relief of the Samoan Islands above the sea floor, and the presence of the northern part of the Tonga Trench to the south-west, gives rise to marked gravity anomalies. A detailed geophysical survey has not yet been carried out, but the anomalies are sufficiently large to be detected by and to complicate normal surveying methods. The following account of such effects was supplied by Mr I. Stirling, Chief Surveyor, Lands and Survey Department, Apia.

"In 1953 the Government of Western Samoa decided that a controlled aerial survey was a prerequisite to the orderly economic development of the Territory and accordingly invited the Surveyor-General of New Zealand to initiate and accept overall control of such a project.

"One of the requirements for the standard traverse was that bearings should be checked at every 10 to 15 stations with main astronomical azimuth stations every 10 miles. However, once actual traversing was commenced it was found that the dense foliage precluded use of check bearings and that it was necessary to observe stellar azimuths at nearly every check station. During the reduction of these observations anomalies were found and a careful independent check indicated that a large gravity anomaly existed.

"The initial station for all surveys is Lemuta, which is situated on the Mulinu'u peninsula at Apia. The latitude of Lemuta was fixed by the Germans in 1911 by meridian observations on several nights to a good many stars, from which were selected about 8 pairs to give a mean value of south latitude at 13° 48′ 26·1″.

"From Lemuta, standard traverses had been run in past years to the east as far as Falefa and in the other direction around the western tip of the island to Salamumu on the south coast. The gravity anomaly showed up most clearly from Salamumu along the central portion of the new south coast traverse nearly opposite Apia. The direction of the road and the clearing allowed observations only to prime vertical stars and this was perhaps fortunate as it is in reducing these observations that use of an incorrect latitude gives differing result from east and west stars.

"For example, at station LIX, which is directly opposite Apia, the following results were obtained:

Star	Direction	Observed Altitude	Result Bearing R.O.
α Leonis	West	19° 13′	107° 53′ 28″
α Leonis	West	14° 25′	107° 53′ 36″
σ Sagittarii	East	30° 54′	107° 54′ 37″
π Sagittarii	East	33° 27′	107° 54′ 34″

"The calculation of the latitude of LIX through the traverse from Lemuta was correct, and the subsequent closure of 113 miles of traverse showed the accuracy to be about 1/15,000. Constant differences between east and west stars indicated that there was a fairly large deflection of the plumb line of about 25″ equal and opposite on the north and south coasts.

"In addition to this, as traversing progressed it was found that all bearing corrections were subtractive. This was very useful because any opposite sign corrections were immediately suspect, but as all traverses were run in an anti-clockwise direction around the islands the consistent correction sign was a further indication of the existence of an anomaly.

"It was decided then to check the Lemuta atitude and to make a complete determination at

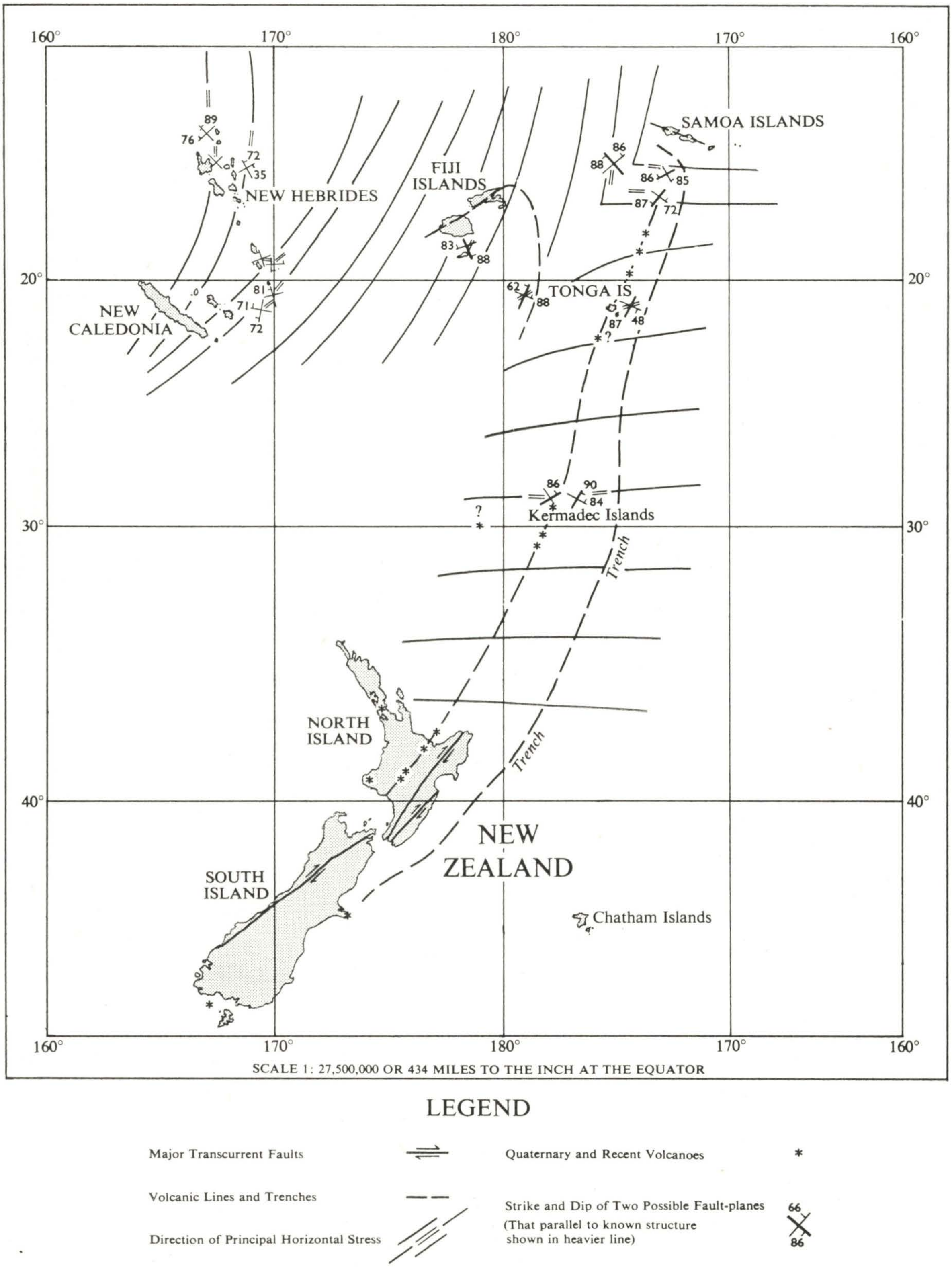

Fig. 36: Stress map, New Zealand-Samoa.

a suitable point on the south coast opposite Lemuta.

"The necessary observations were obtained in August 1954. A Wild T2 theodolite, reading direct to one second, in good order and adjustment was used. In each case large wooden pegs were driven to give stability to the set up. A diagonal eyepiece was available as required and a Wild lighting set was used on all observations. Time was recorded on a half chronometer keeping sidereal time, and it was checked by observations to east and west prime vertical stars before and after the latitude observations.

"The method of circum-meridian altitudes was adopted with an average of 14 observations to each star over a period of six minutes either side of transit. The programme was closely calculated for stars balanced within 30 minutes of altitude and because of the constant threat of cloud several stars in the same altitude range were included. In the final result three pairs of stars were obtained on the Lemuta check and five pairs at traverse mark CV at Poutasi.

"It was not possible to make the observations at Lemuta itself, so a satellite station (01·6 seconds south) was established as the observation point. As the three pairs observed at that point did not constitute a complete determination and as the mean had a probable error much the same as the German result the two were meaned for the accepted observed latitude of Lemuta. The five pairs at traverse mark CV gave a good determination at that point. A summary of the observations shows the following results.

"The result confirmed the earlier indications and explained many inconsistencies in old survey work. It may be as well to record that this deflection did not show up in any work near the eastern and western ends of either island. That is not to say that it does not exist but rather that it is somewhat less, and possibly with different components.

"A simple explanation for the 32 seconds may be the great depths shown on Admiralty Chart No. 1829, which shows soundings around 2,200 fathoms only 15 miles offshore. The purpose of these notes is to record the existence and the amount, measured at one place, of this anomaly and it is hoped that a properly equipped observer may sometime be able to carry out more specific and detailed investigations."

Geological History

The bathymetry around Western Samoa indicates that two great volcanic piles have been built up from the ocean floor over a fissure (or fissures) trending 110°. The two piles merge beneath the sea

At I.T. 01·6″ South from Lemuta — Observer, P. M. Berrill

Date Obs.	Stars Observed		Mean from Pair
27/8/54	α Lyrae North β Pavonis South		13° 48′ 28·7″
27/8/54	ζ Aquilae North α Sagittarii South		13° 48′ 22·8″
27/8/54	β Lyrae North α Tucanae South		13° 48′ 24·4″
	Mean		13° 48′ 25·3″
	Mean observed latitude I.T.	13° 48′ 25·3″ S	
	Reduction to Lemuta	01·6″ N	
	New latitude Lemuta	13° 48′ 23·7″ S	
	German latitude Lemuta	13° 48′ 26·1″ S	
	Mean of German and new	13° 48′ 24·9″ S	

At Traverse Mark CV Poutasi (South Coast) — Observer, I. F. Stirling

Date Obs.	Stars Observed	Mean from Pair
11/6/53	γ Bootis North β Triang. Aust. South	14° 02′ 11·0″
29/8/54	α Aquilae North G Scorpii South	14° 02′ 11·4″
29/8/54	o Herculis North α Pavonis South	14° 02′ 09·8″
29/8/54	ζ Aquilae North α Sagittarii South	14° 02′ 13·4″
29/8/54	α Lyrae North δ Pavonis South	14° 02′ 11·1″
	Observed Latitude Mean	14° 02′ 11·3″
	Latitude CV calculated from Lemuta (above) =	14° 01′ 08·1″
	Difference = twice deflection =	01′ 03·2″
	deflection =	31·6″

and project above sea level as Savai'i and Upolu Islands.

They first appeared, possibly in the late Tertiary, as broad elongated shield-shaped basaltic volcanoes. The shore line of this early phase was at least 600 ft below present sea level, and may have been as much as 3,000 ft lower (450 fathom bench, p. 32). At first only primitive olivine basalts were erupted, but during the closing phases differentiated lavas appeared, more femic or more siliceous, and porphyritic. These early eruptions are represented by the Fagaloa Volcanics, and the differentiated lavas by the trachytic and andesitic members.

The Fagaloa volcanoes ceased erupting during the late Pliocene or early to middle Pleistocene, and at the time may have stood about 6,000 ft above the ocean. Under heavy tropical rainfall they were soon covered with soil and dense vegetation. During the early to middle Pleistocene, streams and rivers carved deep into the slopes, and formed great amphitheatre-headed canyons, which later merged to produce a steep rugged terrain of narrow razor-backed ridges and sharp peaks. A few remnants of the lava slopes remained. The terrestrial debris and long-continued wave erosion built a platform offshore, 600 ft below present sea level, on which corals grew and flourished. Although evidence from other lands reveals considerable glacio-eustatic changes in sea level during the middle Pleistocene, very little exists in Samoa. Only a single bench, imperfectly measured as 130–200 ft above sea level, was noted as being restricted to Fagaloa rocks.

The relative quiet of the middle Pleistocene erosion period was ended by volcanic activity along or closely parallel to the ancient Fagaloa rift. The earliest of this activity may have been during the Penultimate Glaciation, but the earliest of which there is certain evidence is represented by the Vini Tuff and occurred at some time in the Last Interglacial period. Littoral and marine eruptions threw up tuff cones around the coasts (Vini Tuff), and Salani olivine basalt flowed down the valley walls, and across the reef flats and the submarine shelf, burying many of the earlier-formed tuff cones. Vast quantities of lava were erupted, and built the Salani volcanoes to over 3,000 ft above sea level in Upolu and over 4,000 ft in Savai'i. The lava floods buried most of the crest of the ancient mountains, but failed to cover remnants in eastern Upolu that still project as steep, mountain ridges. They buried earlier Pleistocene reefs, built wide submarine slopes, and increased the width of the islands to much their present outlines.

Coral reefs were built up around the Salani lava slopes (represented now, for instance, by the buried fringing reef in the Afia well, and the buried reef at the east coast of Savai'i, p. 41). Narrow reefs probably formed also around the steep Fagaloa coasts, and all were controlled by a Last Interglacial sea level that was higher, but probably not more than 50 ft higher, than the present one. Landward, the Salani lava slopes became dissected by alias and gullies, and, where buried ridges of Fagaloa rocks favoured concentration of ground water along perched water tables, more rapid stream erosion of the thinner cover of Salani flows ensued.

As the warm climate of the Last Interglacial deteriorated and sea level fell, increased erosion probably hastened the development of the spectacular amphitheatre-headed canyons of south Upolu and Savai'i. During the subsequent Last Glaciation the very extensive Mulifanua lavas were erupted. They spread over large areas of western Upolu, and built a great submarine fan off Cape Fale'ula, where the 25, 40, and 100 fathom shelves were buried. They built up the Savai'i uplands by several hundred feet, and built up most of western Savai'i above sea level. They spilled over the heads of the Salani canyons in great fire falls, and partly filled the canyons. Probably vast quantities of Mulifanua lavas poured down the south-west slopes of Savai'i and built up a great submarine fan in the ocean deep that lies offshore, whilst more lavas buried a wide barrier reef on the east coast of Savai'i. Littoral and submarine cones occur in Apolima Strait where the lavas entered the seas.

Probably when sea level was at its lowest during the Last Glaciation, portions of the flanks of the volcanoes subsided on a vast scale, as a result of the changed ground-water conditions in the deeply buried ash and tuff beds. A large segment of the northern part of Savai'i collapsed *en masse* as much as 500 ft. The flanks of south-west Savai'i and of south-east Upolu probably collapsed in much the same way, the former by at least 100 ft, and the latter by an unknown amount. Immediately after, Mulifanua lavas spilled over the fault scarps in Savai'i.

The post-Glacial rise of sea level was so rapid that growing barrier reefs could keep pace only on the gently sloping Mulifanua lavas and elsewhere were drowned. The few aa-rich basalts that were erupted at this time are referred to the Lefaga Volcanics.

When sea level had risen almost to the present position, Puapua lavas erupted in south-east Savai'i (e.g., Palauli, Taga, and Tafua), and flooded out over a wide barrier reef. Sea level continued to rise to the 15 ft level of the Nu'utele Sand, and, as indicated in Tutuila by Daly (1924, pp. 124–5) and Stearns (1944, pp. 1309, 1313), possibly to a height of 20–25 ft above the present level. This occurred some 4,600 years ago. Sea level then fell to the 5–6 ft Tafagamanu level, ca. 2,300 years ago (p. 47). Narrow benches, beaches, and deltas were formed by wave and stream action; and from Pu'apu'a towards Mauga, from Sasina towards 'Auala, and about Falealupo and Fagafau (all in Savai'i) extensive lava flows covered the reefs and the 5 ft Tafagamanu beaches. Puapua lava cascades and fire falls occurred over the cliffs near Falelima, and a few small flows filled valleys in Upolu (Lauli'i, Soaga, Lefaga).

During or after these latest Puapua eruptions, sea level again fell to its present level. In historic time, volcanic activity recurred near A'opo in Savai'i (about A.D. 1760 according to Thompson 1921, p. 52), a submarine eruption occurred in the eastern part of the archipelago, between Tau and Olosega (in 1866 according to Stearns, 1944, p. 1331, in 1867 according to Lyell, 1868, p. 409), and several eruptions took place on Savai'i from 1902 to 1911. The progress of these latest eruptions is described by Jensen (1907) and others.

Figure 37 illustrates the relation between those sea-level fluctuations that are important from the point of view of Samoan geology, and the presumed ages of the several rock formations.

Evolution of the Samoan Archipelago

Chubb (1957) in considering the pattern and development of some Pacific island chains, described an idealised sequence of events, from the first appearance of the volcano above the sea, through stages of erosion and reef formation, with gradual local subsidence to the end product as an atoll. Chubb considered that the older islands and atolls are commonly found at the west end of most island chains. The rate of subsidence of the islands is small; results from deep drilling on Eniwetok indicate a rate of 20 metres per million years (Kuenen, 1954). The former shallow position has been shown by the discovery of Cretaceous reef corals from a mid-Pacific guyot (Dietz, Menard, and Hamilton, 1954), and of Tertiary

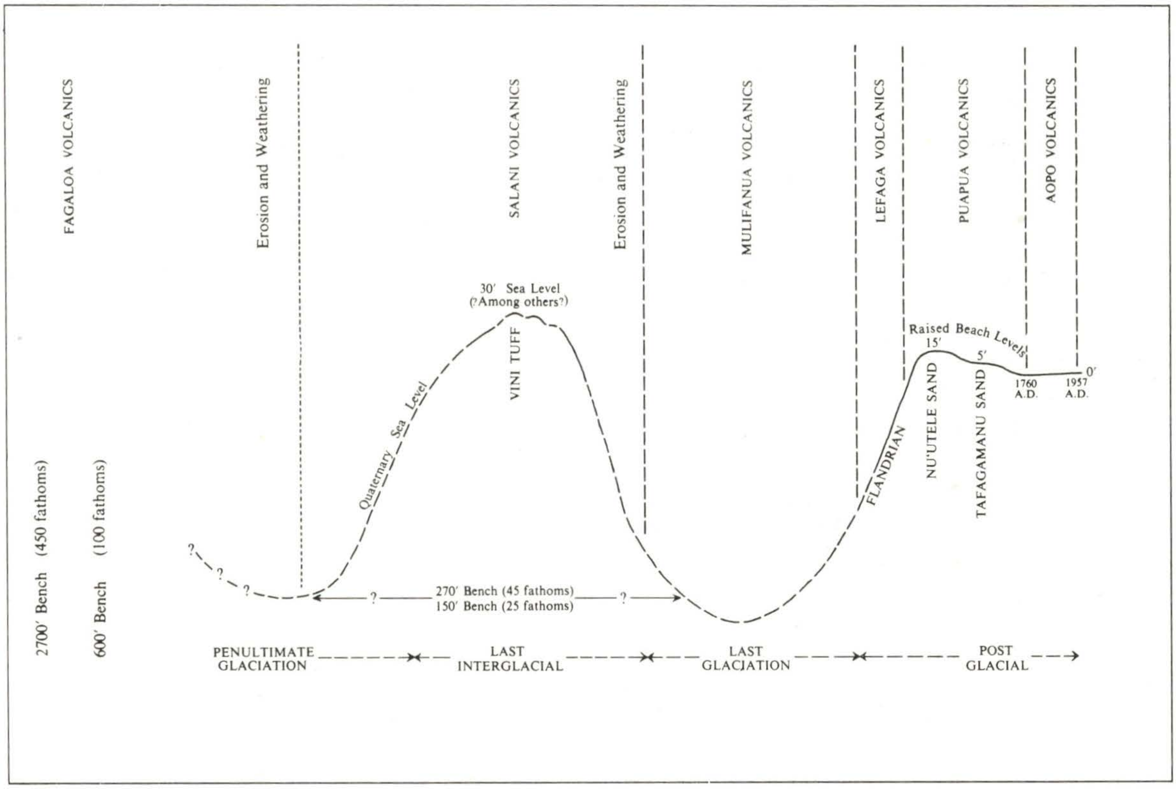

Fig. 37: Age relation between the late Quaternary sea-level fluctuations and the eruptions of the several volcanic formations. No attempt has been made to present the sea-level changes in other than very broad outline, and the diagram is not to scale. As shown in the figure, it is not certain when the 25- and 45-fathom benches were formed; but they are both thought most likely to date from the Last Glaciation.

corals in drillholes on Bikini and on Eniwetok (Emery, Tracy, and Ladd, 1954).

The Samoan island chain differs from all others, first, in that the pattern is reversed, with the youngest volcanoes at the west end, and the only atoll (Rose Island) at the east end, and secondly that the general progression of volcanism along the chain (to the west in this case) was departed from when a submarine eruption occurred near the east end of the chain between Tau and Olosega in 1867–8).

Possibly these departures from the idealised sequence are due to the archipelago being closer to the circum-Pacific fold region than most other chains, and to the unique relation of the main alignment to the neighbouring fold and stress directions (fig. 36).

CHAPTER 5—ECONOMIC AND ENGINEERING GEOLOGY

General

The most important item in the economic geology of Western Samoa is ground water, especially from the viewpoint of future development. Although ground water use and investigations are still in the earliest stages in the Territory, the subject requires a full and detailed treatment, and is presented in Chapters 6 and 7.

The only other deposits entering into the economy of the Territory are roading and construction materials, and while some care is necessary in selecting suitable ash or cinders for roading, or gravel or sand for concrete aggregate, such materials are relatively abundant in Samoa, and their availability presents few problems that cannot be solved by good technique and satisfactory equipment, such as bulldozers, crushing, screening plants, etc.

As part of New Zealand's contribution to a search for phosphate deposits in the Pacific on behalf of the British Phosphate Commissioners, the writers tested in the field and collected for analysis any materials likely to be phosphatic. The field kit-set was provided by New Zealand Dominion Laboratory.

Phosphate Survey

The only rocks considered at all likely to contain phosphate minerals in economic quantities were those herein mapped as Vini Tuff. Samples of waste organic matter from the lava tunnels at Tapu'ele'ele, Savai'i, and Falemauga, Upolu, were thought to be possibly phosphatic, but tests gave negative results. The occurrence of Vini Tuff is restricted to the islands Nu'utele (Vini), Nu'ulua, Namu'a, Fanuatapu, and Apolima, and to Cape Tapaga in south-east Upolu. The lithology varies only slightly, the greatest variation being found at Cape Tapaga where a 6 in. bed of cemented coral sand, dipping at 20° towards 030°, is interbedded with normal tuffs some 20 ft above sea level.

Hand specimens of the tuff showed such a predominance of basaltic material that workable deposits seemed out of the question. Nevertheless, quinine molybdate spot-tests with a field testing-kit showed positive reactions on calcareous samples from Vini, Fanuatapu, Cape Tapaga, and Apolima.

In the light of these results, further grab samples were collected and later analysed at the Dominion Laboratory, Wellington, New Zealand (Table 5). Cemented beach sand from Tuasivi was also analysed, but contained only a negligible amount of phosphate.

TABLE 5. Phosphate Analyses

Field No.	Locality	P_2O_5 Per Cent
AC. 2358	West side Nu'utele (Vini) Island ..	0·4
WS. 522	Cape Tapaga, 20 ft above sea level ..	0·42
,, 539	Six grab samples, Nu'utele (Vini) Island	0·39
,, 617	East headland, Apolima	0·40
,, 618	Apolima spring, 15 ft above sea level ..	0·46
,, 619	Apolima light, 200 ft above sea level ..	0·14
,, 623	Cemented beach sand, Tuasivi beach ..	0·09

Marshall (1927, 1930) presented analyses of basalts in New Zealand's dependencies that averaged 0·3 per cent P_2O_5; and seventeen analyses of volcanic rocks from Tutuila, Upolu, and Savai'i averaged 0·5 per cent P_2O_5 (MacDonald, 1944, p. 1357, pt. 359). Thus the Vini Tuff phosphate analyses shown in Table 5 show that that formation is no more phosphatic than any normal volcanic rock of that part of the Pacific. The tuff is certainly not a workable source of phosphate.

Engineering Geology

Brief observations on the geological conditions at a few large waterfalls for which hydro-electric development is possible, as well as notes on the almost completed Alaoa installation are presented below. The possible schemes are in the Fagataloa and the Soaga river systems of Upolu. It should be stressed that the flow rates given are very approximate, and accurate gauging throughout at least one year is desirable.

Fagataloa System

Three schemes are possible, involving structures at Afulilo Falls and Fuipisia Falls in the Vaigafa tributary, and at Sopo'aga Falls in the main river.

AFULILO FALLS

The fall is approximately 170 ft high, nearly vertical, and at the time of inspection (19 October 1956) the stream was flowing at an estimated rate of 5 cusecs ($2\frac{1}{2}$ million gallons per day). From the appearance of the fall lip, this was a low flow and the average rate could well be twice as great. The full head, at 5 cusecs, should yield some 50 kilowatts of electricity at 70 per cent efficiency (obtainable with a Pelton wheel).

The flow would be much increased by constructing a low dam (5–10 ft) close to the fall lip, and using the flat high-level Afulilo basin for storage. There is little likelihood, as locally suggested, that water from any such artificial lake would leak northwards into Fagaloa Bay and possibly cause damage. The surface Fagaloa rocks are generally impermeable. Any channel-ways within the Salani lavas would most probably be sealed by the clay in the swampy ground upstream of the falls, the deeper Fagaloa rocks themselves would probably be sealed from the Salani by a thick buried soil layer (see fig. 25), and Fagaloa dykes would form an additional seal.

The rocks at the fall lip, mapped as Fagaloa Volcanics, consist of compacted brown ash, and interbedded hard dense porphyrite, intersected by a number of fine-grained basalt dykes dipping 80–90° north. This combination of rocks is especially impermeable, and should be sufficiently stable to carry an intake structure connecting to a penstock down the cliff face. However, the rock should not be shocked unduly by blasting, otherwise leaks may be started. A short race may be needed to carry the water from the fall along the hill face to the penstock. If so, provision must be made to seal completely the lining of the race and intake, as the rocks are not uniformly impervious, and an artificially induced leak might have serious consequences.

The valley floor immediately below the fall consists of similar rocks and should provide good foundations for a small powerhouse.

Access is at present afforded by the western part of Richardson's Track from the road on the east side of the Vaigafa Bridge, and for the hydroelectric works a short road could be constructed readily along the south-east side of the Vaigafa River to the foot of the fall. Material for concrete aggregate is plentiful around the foot of the fall, and will require only crushing and screening.

FUIPISIA FALLS

The fall (see fig. 38) is 185 ft high, vertical, and at the time of inspection (25 October 1956) was flowing at about 10 cusecs (equivalent to 109 kilowatts at 70 per cent efficiency).

The rocks at the fall lip consist of a strong ledge of basalt (Salani group) at least 8 ft thick, underlain by interbedded massive basalt sheets and porous blocky aa and scoria beds, all dipping south at between 3° and 5°. The stream, for several chains from the fall lip, flows on the same basalt sheet. The basin below the fall is floored with

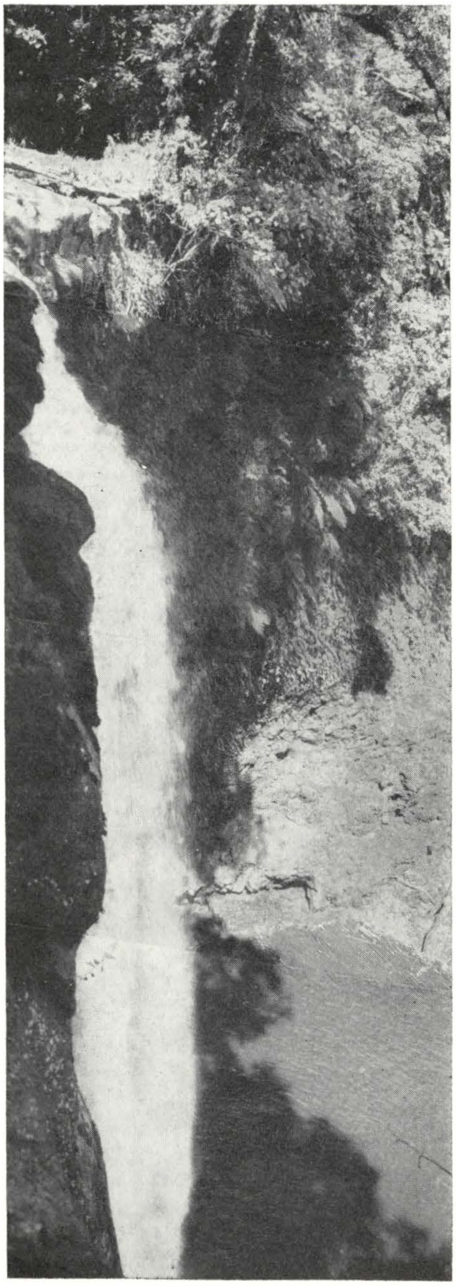

Fig. 38: Fuipisia Falls (185 ft), Vaigafa River. Fall-maker rocks are Salani basalts.

reddish weathered scoria resting on porous basalt, which around the foot of the enclosing cliffs is blanketed with fans of rubble.

The rock at the fall lip should provide a good foundation for an intake structure, although very great care will be necessary to avoid fracturing the basalt sheet by blasting. It may not be possible to install the penstock close to the fall, and a race may be required to carry the stream south-eastwards for 2 to 5 chains along the basin rim. As at Afulilo Falls, full provision should be made to seal any such race entirely, as the underlying rocks will not be completely watertight, and blasting should be kept to a minimum, using only small charges.

The only feasible site for the powerhouse appears to be in the basin below the fall, and access to it is difficult. It will be necessary to excavate the rubble on the powerhouse site to reach firm rock for foundations. Access to the fall will be possible by constructing a short road west of the main Falefa–Aleipata road, and for access to the basin it will probably be necessary to construct a short steep road into the downstream end.

Sopo'aga Falls

The falls consist of two drops, an upper one of about 30 ft and a lower one of 160 ft. Between them the river flows in a short deep chasm 10 to 20 ft wide and 70 ft deep, and below the larger fall this opens out into a steep-walled basin. The rocks, mapped as Salani Volcanics, consist of two superimposed sheets of hard dense basalt, separated by weathered red and grey aa. The upper basalt sheet is also overlain by 2–5 ft of aa, along the edges of which there are numerous springs in the stream channel.

It may be possible to construct an intake at the lip of the upper fall. This would necessitate a flume or pipe in the chasm and fall-basin, the placing and anchoring of which would present great difficulties. It will be almost impossible to confine the river by a dam at the lip of the lower fall, as the walls of the chasm will certainly leak to some degree, especially along the porous beds. The type of structures to be used will depend on the possibility of working in the confined space of the chasm. They may range from a simple intake with a long flume or pipe supported along the walls of the chasm and the basin, to a large concrete flume lining the chasm, with possibly a small dam at the lower end.

The rocks appear to be sufficiently dense and stable to support quite large structures. A powerhouse sited in the basin will present difficulties of access, and will necessitate excavations for foundations through the rubble in the bottom.

Soaga System

Only a brief examination of the Soaga system was made during a traverse inland to Fale o le Fe'e and to the mountain crest beyond (27 August 1956). Although several falls occur in the headwaters, and may be usable, only the well known Soaga Falls were inspected.

Soaga Falls

These are approximately 50 ft high, and the flow was estimated at between 20 and 50 cusecs. The estimate may be considerably in error as the falls were seen only from below. The falls are some 1,500 ft above sea level. Above them the stream is confined in a deep valley with a steep gradient and several cascades; below, the stream is less steep and has small flats alongside.

Rocks at the falls, mapped as Fagaloa Volcanics, consist in downward order of 20 ft of flat-cleaved fine basalt, 20 ft of soft, compacted brown ash, 5 ft of blocky basalt, and 40 ft of compacted brown ash. These beds all dip at 30° north-west. The ash beds appear relatively impermeable, but the basalts are probably pervious owing to the strongly developed cleavages and blocky jointing.

The rocks are generally stable, and conditions would favour a small intake structure at or above the fall, with a pipe laid on the stream flats below, taking water to a powerhouse located some distance downstream. Again, it will not be possible to install any large impounding structure, and the use of explosives should be kept to a minimum.

In the future hydro-electric development of the Soaga system, consideration should be given to the possibility of piping water from several falls to a single generating station located some distance downstream. Access is at present difficult, and would have to be provided during construction by extending the hill road east of Alaoa power station, between the Soaga and Vaisigano Rivers.

Alaoa

The Alaoa power scheme taps two branches of the Soaga, by means of races along the hillsides, and a forebay and penstock above the powerhouse. Construction was almost completed at the time of inspection (24 October 1956), and it only remained to seal the races and forebay.

The main race has been constructed along the hillside south of the forebay in basalts and ash beds of the Fagaloa Group. The permeability of these is highly variable, and at various points along

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the race a full concrete lining is required, especially where the hillside below the race is very steep. Any leaks there would result in slips and washouts that would prove expensive to repair.

The forebay is excavated on the spur between the two branches of the river behind and above the powerhouse. The slope of the hillsides below the forebay, especially that to the north-west, is steep (at least 50°), and is a possible point of weakness from slipping due to leaks from the forebay, or even from runoff caused by excessive rainfall. Every precaution should be taken to ensure that these slopes maintain their stability, and especially that the forebay does not leak.

The Director, Public Works Department, has proposed that the forebay be lined with concrete slabs separated by watertight rubber gaskets, and that the floor be tile-drained, at 3 ft intervals, with the outflow located near the penstock intake.*

These measures, together with regular inspections, appear to be adequate. It would be desirable, during the early stages of operation of plant, to have daily inspections of the forebay retaining walls, and the drain outflows, and at least every second day an inspection of the main race. These daily inspections should be maintained for several months, if possible a year, and thereafter could be carried out at longer intervals.

The first signs of leakage through the retaining walls or from the drain system should be attended to immediately by the engineering staff. As a safeguard, should repairs become necessary, it would be desirable to construct an emergency bypass of the forebay.

* This has been done (12 November 1957).

CHAPTER 6—THEORETICAL SOURCES OF WATER

Introduction and Explanatory Description

Introduction

Future development in Western Samoa depends to a considerable extent upon an adequate supply of water being available for domestic and agricultural purposes. Present supplies are meagre, and are virtually confined to the coast. Even there, however, the presumed increase in population will strain the present supplies further, and inland development cannot be undertaken on a large scale without an assured water supply.

The following chapters are therefore directed to a survey of the hydrology (water supply) of Western Samoa. Initially some explanatory descriptions of water-supply principles are given for the benefit of the non-technical readers within the Territory; and the present chapter is concluded with a review of the sources of water that are theoretically available for development, and of the supply potentialities of the several volcanic formations. The final chapter reviews the present supplies and future requirements of the Territory, and recommends specific sources for individual areas.

Rainwater Cycle

Water vapour in the clouds is precipitated as rain, and falls most heavily on the higher land or on those parts of the Territory that face the prevailing wind (i.e., the eastern ends of both islands – fig. 39, a). On reaching the ground, some of the rainwater is returned to the atmosphere by evaporation or by plant transpiration (b), some of it runs off the ground surface into streams and thence to the sea (c), but in Samoa probably the majority of it passes through the soil and the sub-soil into the rock below (d). This water descends to a level below which all voids in the rocks (fractures, spaces between sand grains, original or solution cavities, etc.) are completely filled with water (e). This vast body of water contained in rock voids is known as the ground water. Its upper surface (the "water table" (f)) descends gradually seawards to coincide with sea level at the coast. That part of the ground water that is above sea level moves slowly, as a body, through the rock voids to the sea. At low tide this fresh water can be seen emerging from numerous springs all around the coast (g).

Where the ground surface has been eroded down to below the water table there will be lakes or flowing streams (h). However, after a prolonged dry period the ground water is greatly reduced in total volume, since it escapes to the sea at a relatively constant rate regardless of the season. The water table drops accordingly, and when it descends below the base of the valleys, the streams will dry up (i).

Where a valley has an amphitheatre head and the valley floor is below the water table, water will emerge from the valley side as a spring and flow seawards as a stream.

Any well ("well" will be used below as embracing both wells and drillholes) that descends below the water table will have water in it below that level (j, k). With the seasonal fluctuation of rain supply, however, the water table may descend temporarily below the bottom of the well, when the latter will become dry (l). Deepening would eventually find the water again.

The equilibrium of the ground-water cycle can be disturbed by bush clearance, which allows greater rates of evaporation and correspondingly reduces the run-off and the recharge to the ground water. This results in a local lowering of the water table and a decrease or disappearance of surface or spring water. Thus water reserves are desirable in some important catchment areas.

Water-table Depth and Ground-water Gradient

The ground-water gradient is the rate of descent of the water table towards the sea. Highly permeable rocks will have very low gradients (fig. 39, m), of the order of 1 to 5 ft per mile (e.g., cavernous limestone at Niue, Schofield, 1959; and fractured and loose basaltic volcanics at Hawaii, Stearns, 1940). The younger volcanics of Western Samoa will probably be similar. Relatively impermeable rocks on the other hand (e.g., clays, and unjointed lava flows and dykes), can have very steep gradients (n). In some dykes gradients may be nearly vertical (o), and high water-table levels have been noted on their landward sides in Hawaii (Stearns, 1940). This confining effects of dykes is unlikely to be important in Western Samoa, however, since dykes are known to be near the surface only in the Fagaloa Volcanics. These rocks are less permeable than those of the younger formations, and thus have relatively high water-table levels as well as surface water supplies. Hence water is seldom in short supply and ground water is never deep in areas of Fagaloa rocks.

A knowledge of ground-water gradients is most desirable, since it enables the depth to water table to be extrapolated away from the known areas. It thus permits estimates of the minimum depth to which wells must penetrate below the water table to contain water. Unfortunately, such knowledge will only be gained in Western Samoa after several more wells have been sunk under differing conditions. In the meantime, very low gradients (measurable in a very few feet per mile) should be suspected in the younger volcanics that cover the majority of the Territory. This effectively means that wells will need to be sunk almost to sea level to reach water (p). Apart from areas of the oldest rocks (Fagaloa or older Salani), where the streams are virtually permanent, the water table will be close to the surface only near the coast, or close to "buried hills" of older rocks (q).

Perched and Artesian Water

The path of rainwater from the ground surface to the ground water may be impeded by some impermeable bed, and the rock voids immediately above this bed will become full of water. The resulting body of "perched water" (fig. 39, r) has similar properties to the ground water (e.g., springs will occur where it is cut by the ground surface and wells sunk into it will contain water below the level of the "perched water table"). Any body of water that is anomalously high should be suspected of being perched. A body of perched water may be drained by fracturing the impermeable rock by blasting, or by drilling and failing to case a hole through it.

Artesian water is confined below an impermeable bed of rock. In Samoa, artesian conditions could exist where an impermeable bed of unfractured lava overlies a permeable bed of aa (fig. 39, s). As the two beds dip seawards, normal hydrostatic head will build up pressure in the aa, and fresh water should rise high in any well or drillhole that penetrated the lava (t) – it might even overflow. Where a natural fracture occurred in the lava, a spring might result, even as a fresh-water spring offshore (t).

Relation of Fresh to Salt Water

Rainwater replenishment ensures that a body of fresh ground water exists below every island. Fresh water is slightly lighter than salt water, and "floats" on top of it as a lens-shaped body. Theoretically for every foot of fresh water above sea level, there will be 40 ft of fresh water below it before salt water is reached (fig. 39, v).

Unfortunately this simple picture is complicated by two factors. Firstly the division between the salt and fresh water is not sharp, but is a zone of mixing (w), which contains water that would be useless for human consumption. Secondly the tidal effect makes the rule difficult to apply near to the coast (where its application is most important) if the ground-water gradient is low.

For practical purposes it is best to use the rule in a qualitative sense only, i.e., to realise that salt water will exist below fresh water and may be tapped accidentally by drilling too deeply where the water table is close to sea level. It is a general rule that although drillholes with pump intakes below mean sea level may yield fresh water for a long time at high pumping rates, they are liable to yield salt water eventually (x), and will take a long time to recover (Brown, 1925, p. 47). To avoid such dangers in Samoa it is most important that any wells used for high rates of pumping should have their pump intakes no lower than mean sea level.

Rainwater

Rainfall in Samoa (Curry, 1955) is high – few areas receive less than 100 in. a year, and extremely few under 50 in. Fortunately the areas of relatively low rainfall are close to the coast, and in the higher country, where rainwater may well prove most important, the rainfall is 100 to 300 in. a year. As an example of the quantity of water available: a rainfall of 140 in. a year (only 20 in. higher than coastal Apia) would yield an average of 1,000 gallons of water per day from the roof of a building with an area of 5,000 sq. ft. (roughly the size of a normal Samoan village church). Such a quantity is in excess of present consumption at many villages in the dry season.

Because of its simplicity, its negligible operating costs, and its availability at the villages themselves, rainwater catchment may well prove a most important source of water supply in Samoa. It will be particularly valuable in much of the higher country where surface water is absent and ground water is deep. It may, in fact, be the only practicable or economic method of obtaining water in such areas. Rainwater catchment will be valuable also as a temporary means of improving the supply to some villages. Often this will require no more than repairs or extensions to existing installations.

At present many villages have rainwater tanks of some sort, but only in a few exceptional cases is water available from these tanks in the dry season when it is most required, and many of the installations are no longer watertight. Not all the reasons for the present paucity of rainwater supplies are technical, although an infallible technique of sealing leaks in concrete tanks under Samoan conditions is essential. However the success of the roof-catchment scheme at the Vaiola Mission Station in eastern Savai'i, where under half the available roof area is utilised, shows that the system can be made to operate efficiently in Samoa. Some changes in traditional architecture (which includes thatched roofs for the houses – *fales*) might be essential for the introduction of schemes that involved large quantities of water.

Rainfall records are essential in the planning stages of any scheme if adequate water is to be assured. The minimum area of roofs to supply a given quantity of water per annum to a village community can be calculated if the range of annual rainfall is known. In practice it is desirable to exceed this minimum, and to use as great an area as possible, since this makes the fullest use of any rain during the dry season, and thus reduces the necessary storage volume. The total volume of storage tanks that is required can be calculated relatively simply if the rainfall distribution throughout the year is known, together with the total available roof area. Clearly, therefore, it is more important to know the distribution of rainfall throughout the year, and especially in the dry season, than it is to know the bare figures of annual rainfall.

Rainwater is a source of clean water provided that tanks are covered and the installation is kept in good repair. In Samoa it may be of vital importance in supplying domestic and agricultural water to inland villages. Provided that agricultural uses are not intensive, that the roof areas of all houses are used, and that ample storage is provided, it appears that no water shortage will result.

Surface Water

Distribution

Surface water is of very restricted occurrence. Lakes are confined to inaccessible craters and to brackish swampy coastal areas. Permanent rivers and streams are restricted almost completely to areas of Fagaloa and older Salani rocks, and in the case of the latter formation, streams and rivers often fail to reach the sea (e.g., Vanu and Mali'oli'o Rivers in Savai'i). In a few cases streams do travel over younger rocks where the cover on these two older formations is thin (e.g., the Lata River seawards of Sili in south Savai'i). Thus usable surface water is virtually restricted to the north-eastern quarter of Upolu, the larger stream and river valleys of south-eastern Upolu, a few streams east of Falelatai in south-west Upolu, a few of the largest river valleys well inland from the eastern coast of Savai'i, a small area south-west of Fagamalo in north-east Savai'i, and a wide area inland from Palauli and Sili in southern Savai'i. Elsewhere, valleys themselves are of restricted occurrence. Some contain water only in the wet season, others only after heavy rainfall, and still others only after torrential downpours that occur only at intervals of several years.

Development

Most existing Samoan piped water supplies depend upon surface water and gravity reticulation. The development and use of surface water pose engineering rather than geological problems, and therefore need be considered only briefly here. The well known problems of pollution will be excluded.

Stream gauging prior to installation is an essential feature of surface water development. Minimum flows (at the end of the dry season) must be known in order that the limitations of the supply are fully appreciated. Maximum flows should be known so that the intake constructions are protected as far as possible from predictable high floods. Clearly, gaugings over several years are most desirable, which virtually involves the regular gauging of all major streams, regardless of whether they are to be developed immediately or not in order that the information will be available when required.

Ram pumps are used to a minor extent in Samoa at present for small supplies. In the future, when suitable gravitational schemes are fully developed, major pumping of surface water may be required.

Springs

Inland Springs

Inland springs may occur where the ground surface cuts the water table or some body of perched water. In the majority of cases it is likely to be the latter cause; and therefore care must always be taken, when developing an inland spring, that the ground below the level of the spring is not disturbed too much (e.g., is not shattered by explosives), or the spring may disappear.

Springs may fail towards the end of a long dry spell, and their flow should therefore be measured just before the onset of the rainy season. They may form a useful additional supply to roof catchment in an otherwise unwatered upland area. They will continue to flow well after the dry season has started, and roof tank water could be conserved over this period. For the latter part of the dry season roof tanks could be used, and these will be replenished quickly at the beginning of the rainy season, whilst the spring might be more sluggish in yielding an adequate supply again.

Inland springs are unlikely to contribute much to the final water-supply potential of the Territory except in eastern Savai'i. There the springs at Asaga (almost a coastal spring) and Puna may well be important. Elsewhere, springs will be found rarely by hunters, but no expeditions to seek them out are recommended. Spring water should be tested for health requirements prior to use by a village, especially if villages exist inland from the spring. Usually, however, spring water will be quite safe bacteriologically, although it might contain high concentration of certain mineral salts (notably of iron) when it emerges from young rocks.

Coastal Springs

All rainwater that does not return to the atmosphere as water vapour, or arrive at the sea via a river or stream, must pass to the sea via the ground water. It will be discharged to the sea by countless channelways around the coast, a number of which will be obvious as the springs that are so common along Samoan coastlines. These springs will seldom if ever fail altogether, although those that are highest above sea level may be reduced in flow towards the end of the dry season.

The flow of any spring will depend upon the relative size of the channelway that controls it. The number of channelways is infinite since even the spaces between the grains of sand on the beach are perfectly adequate to allow the passage of fresh water to the sea. Water will flow faster, however, in open cavities such as large rock joints and lava tunnels, which exist especially in the rocky headlands of the younger formations. It is sometimes possible to increase a small flow by blasting. It is equally possible, however, that blasting may create numerous additional channelways and thus dissipate an existing large flow.

Coastal springs supply most Samoan villages with water at present in the dry season. They will always be a most useful stand-by.

As a general rule, it is not practicable to pump coastal springs continuously. The reason is that they are extremely close to sea level (being often below mean sea level at low tide) and therefore the pump suction will either not pump water at low tide, or will pump salt water at high tide. There is no theoretical objection to their being pumped intermittently near the time of low tide only and filling a reservoir, provided chloride determinations are carried out in advance.

Coastal spring water would generally be expected to be bacteriologically pure, although where houses or pig runs are directly inland, tests are obviously desirable before the water is used.

Submarine Springs

In the Mulifanua area, local tradition reports a strong spring of fresh water well offshore. If the report is correct, it is probable that the unfractured Mulifanua lava sheet at the coast continues well out to sea, and fresh water escapes under artesian pressure at the first break (fig. 39, u). Such escapes may be well below low-water mark, and are quite distinct from normal coastal springs. Where their occurrence is confirmed by investigation, it might be rewarding to sink a well near the shore opposite the submarine spring. Large quantities of fresh water could be available at little expense, although the upper part of the well might have to be tightly sealed. Possibly the artesian pressure would be sufficient for limited reticulation.

As with other cases of confined water, the confining bed (here the unjointed lava) should be carefully protected from the fracturing effects of blasting.

Wells

Wells v. Drillholes

The word "well" is used throughout this bulletin to embrace both wells and drillholes. They differ from one another only in their constructional methods and their diameters: a true well is dug by hand or machine, and must be wide enough to allow men to work; whilst a drillhole is put down by a machine and would be of the order of 3 in. to a foot in diameter. Where it is necessary to refer to a true well or a drillhole specifically, the respective terms "dug well" and "drilled well" will be used.

Drilled wells, of which there are none in Western Samoa, have the advantages of ease and speed of construction, and (in New Zealand) of cheapness, although the latter might not apply in Samoa where labour traditions and costs are substantially different. It is probably true that drilling will be the only practicable way of putting down the deepest holes, although apparently no great difficulty was experienced in putting the Afia well down its 130 ft. Drilling rigs are usually truck-mounted and therefore temporary roads might be needed to the drilling sites. Water is necessary to cool the bit and to remove cuttings. Some water would therefore have to be either piped to the drill site or carried there by a watertruck.

Dug wells have an advantage in allowing access for inspection and cleaning. They also yield somewhat more water, but the increase is by no means proportional to the increase in diameter (e.g., a fourfold increase in diameter might produce 25 per cent more water). However, since it is possible to gain access to the water table in a dug well, it is possible to "develop" the well, i.e., to drive horizontal tunnels at that level and thus increase the flow considerably.

Drawdown and Yield of Wells

When a well has been standing idle for some time, the water level in it will correspond to the water table in the surrounding country. As soon as water is pumped from the well, however, the water level in it will drop. At any steady rate of pumping the water level will eventually again become stationary at a new lower level, and the difference between this level and that prior to pumping is known as the drawdown. For every well the drawdown is roughly proportional to the rate of pumping; and although the relationship is by no means simple in certain cases, the measurement of drawdown in a well for a given rate of pumping enables the maximum yield to be estimated roughly. For example, if the depth of water in a well is 4 ft, down to the pump intake, and the water level drops 6 in. when pumping at 600 gallons per hour, the maximum yield of the well (i.e., when the drawdown is 4 ft) will be 4,800 gallons per hour, or thereabouts. When pumping ceases, the water in the well will slowly rise to water-table level.

The drawdown for a given rate of pumping will vary from well to well inversely as the permeability of the water-bearing bed, or "aquifer". In impermeable clayey strata, or unjointed lava, for example, the drawdown might be 50 to 100 ft for rates of pumping of 200 gallons per hour; while in very permeable gravel or aa, the drawdown for a similar pumping rate might only be a fraction of an inch. Drawdowns under Samoan conditions are expected to be very low, but will be greatest in the oldest and more weathered rocks (Fagaloa especially, and Salani to a much lesser extent).

Shallow Wells

Reciprocating pumps in a reasonable state of repair will not lift water from a greater depth than 22 ft. (With centrifugal pumps the maximum figure is only 15 ft, and both figures must be reduced if the installations are in a poor state of repair.) It is thus convenient to consider all wells of less than 20 ft in depth as "shallow", since they should be capable of being pumped by a surface reciprocating pump. Wells of such depth are also relatively easily constructed by local labour.

Shallow wells are used at present in many parts of Samoa to obtain fresh water. Since the water table is generally close to sea level and a shallow well is defined as one no deeper than 20 ft, all shallow wells are close to the coastline (and except for rare wells in bodies of perched water, they always will be). They are therefore often affected by the tide: most fluctuate with the tide, and many are brackish at high water. They may be dug in sand or in basalt. In the former case the sides need protection by bricks, boulders, or concrete, and water may have to enter the well through boulders covering the sand base or through porous concrete rings.

No simple rule was found to apply in Samoa with regard to the saltiness of coastal wells. In Fa'asaleleaga (east Savai'i) two wells are sited on Tafagamanu Sand, one 33 and the other 47 yards from the sea. The water in both rises and falls with the tide, but only the former is salty at high tide. A well at Ulutogia (Aleipata), sited $3\frac{1}{2}$ chains inland, yields fresh water. Whilst these figures may be useful in other areas of Tafagamanu Sand, they are not applicable to other rock types.

Shallow wells can usefully yield small supplies, and may be valuable for short-term improvements. They do not usually lend themselves to large-scale development by pumping, however, for if the strata are relatively impermeable the water level will be high but the capacity low, while if the strata are relatively permeable the quantity available will be high but the level will be so close to sea level that the well will probably pump salty water at high tide. Thus shallow wells are restricted to continual use by a village on the bucket-at-a-time principle, to continual use by a small number of people using a pump, or to intermittent use at low tide by a village with a surface pump. A shallow well may sometimes be dug profitably in talus or alluvium inland.

Shallow wells are particularly susceptible to contamination by refuse dropped down them, by animal or human waste on their landward side, or by the breeding of mosquitoes and other insects.

Deep Wells

Only two wells in Western Samoa may be described as deep (i.e., with water level deeper than 20 ft) – the Afia well ($1\frac{1}{4}$ miles inland from the Upolu coast between Mulifanua and Satapuala) and the Mauga village well (in north-east Savai'i, completely surrounded by Aopo lava). In both, the water table is very close to sea level. It was measured by electrical methods in the case of the Afia well, as 127 ft 9 in. below ground level (i.e., 1 ft 6 in. above mean sea level, Mr I. F. Stirling, pers. comm.).

The Mauga well is a little over 100 ft deep, and is about that height above sea level.

The construction of a deep well is a long process, but the result is likely always to be rewarding in Samoa. Afia well took nine months to complete to a depth of just over 130 ft. No accurate record of the strata encountered is now available, and the sides of the well cannot be examined. However, it is reputed that hard and soft beds (presumably lava and scoria) were encountered, and even coral is reported. The well showed no appreciable drawdown (with measurements taken to a fraction of an inch) when pumping at 2,000 gallons per hour. Since there is 1 ft 6 in. of allowable drawdown to mean sea level, the capacity of the well, whilst unknown, is certainly very large.

If a well is yielding insufficient water, it is possible to increase the supply by "developing" it – i.e., by drilling horizontal holes or by driving horizontal tunnels at the water-table level. Wells can also, in special cases, be sunk other than vertically and can in the extreme be put in more or less horizontally to skim the top of the fresh-water lens close to sea level.

The required depth of a well can sometimes be reduced by moving the site towards hills in older rocks, even when this entails climbing higher above sea level (see fig. 39, q).

The sinking of deep wells will certainly become important in supplying water to the Samoan people. The Afia deep well shows clearly the capabilities of this type of supply, which will be especially useful in providing water for areas of relatively low rainfall, or for areas covered by young rocks, where the height above sea level is not too great. Reciprocating deep-well pumps (e.g., at Afia well), work best at depths of 200 ft or less. They can work up to 450 ft with difficulty. Below that depth (and up to 1,000 ft) submersible centrifugal pumps are necessary, and must be driven by electric motors. Hence, in the absence of electricity supplies, diesel generating sets are required to operate these pumps. It would be desirable, therefore, to restrict well sites to those no higher than 400 ft above sea level until more is known of Samoan ground-water conditions.

The quality of water from a deep well should be good, provided that the well is protected from pollution by objects dropped down it. As in the case of shallow wells, the pump intake should not be placed lower than sea level, but this does not mean that the well itself may not be lower. The great supply of water to Afia well came from a bed, presumably of scoriaceous basalt, that was cut below sea level in the construction of that well. However, sinking should proceed cautiously once sea level is reached—a shothole (which could be plugged if necessary) should be drilled ahead of excavations, and continual salinity tests should be made.

Water Potentialities of the Rock Formations

Fagaloa Volcanics

The severe weathering of the Fagaloa Volcanics has brought their water supply characteristics closer to typical New Zealand conditions than any other rocks in Samoa. Surface water is characteristic, and in this hilly country it offers the best source of supply with gravity reticulation. Ground water would generally be shallower, and available in smaller quantities than from younger less weathered formations (although the quantity would probably still be adequate). Springs occur in Fagaloa rocks at a wide range of altitudes, as distinct from those in younger rocks that are only rarely inland.

The Fagaloa Volcanics will be most important in the development of Samoan ground water where they occur as buried hills in the eastern part of Upolu. In the neighbourhood of Tafua upolu the country is without surface water, and if the surface rock types continued to sea level, water would be obtained only at very considerable depth by drilling. However, drilled wells started in younger rocks close to the hills of the Fagaloa Volcanics should encounter the latter rocks at considerably shallower depths than sea level, and water should be available near their upper surface (see fig. 39, q).

Salani Volcanics

Salani rocks may carry surface water, often in relatively large rivers (e.g., Fagataloa in Upolu, and Lata in Savai'i), which are potentially useful. Often the quantity of flowing water diminishes coastwards by underground seepage.

Ground water should be available in quantity from the scoriaceous parts of the flows. Depths to water will vary widely between the shallow conditions (say 20–50 ft) of the Fagaloa Volcanics, and the deep conditions (down almost to sea level) of the Mulifanua Volcanics. Inland springs are likely where these rocks are covered shallowly by younger formations in steep country (e.g., Sala'ilua and Siga springs in Savai'i).

Mulifanua Volcanics

Only rarely does surface water travel on Mulifanua rocks. Most rain water soaks quickly through the surface rock and soil layers and descends to a low-level water table whence it travels slowly to

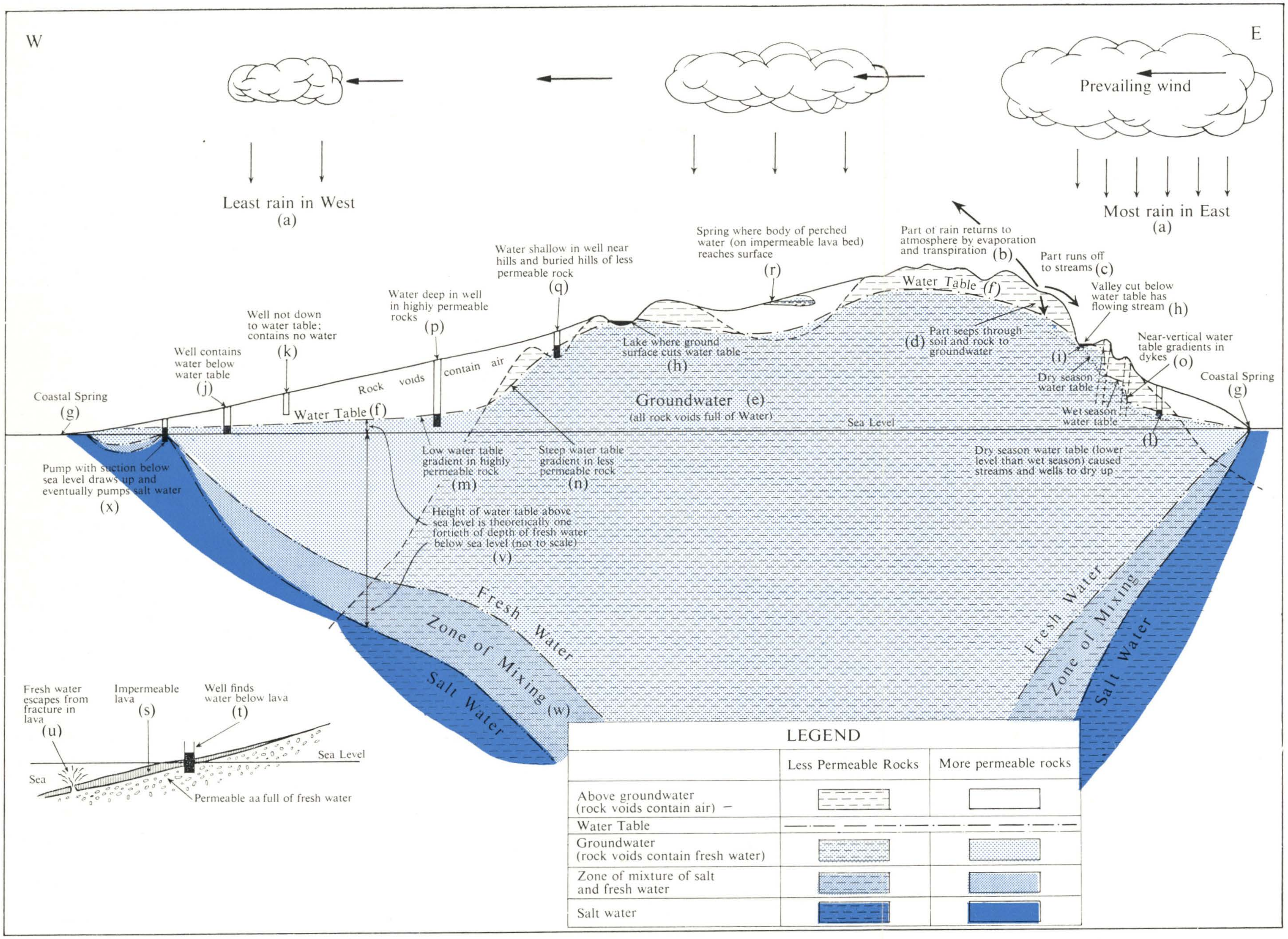

Fig. 39: Diagrammatic illustration of water-supply principles:

The prevailing wind causes more rain to fall on the eastern than on the western side of the islands (a). Part of rain (b) returns to atmosphere by evaporation and transpiration, part (c) runs off into streams, and part (d) seeps through soil and rock to the ground water (e). The upper surface of the ground water (the water table (f)) descends to sea level at the coast where springs (g) occur. Where the ground surface descends below the water table a stream or lake results (h); similarly wells contain water only below the level of water table (j, k). The water table is lower at the end of a long dry spell, when streams (i) and wells (l) may go dry. The water-table gradient is gentle in highly permeable rocks (m), steep in less permeable rocks (n), and nearly vertical in dykes (o); consequently water tends to be shallower nearer hills of older less permeable rocks (p, q). An impermeable bed inland could cause "perched water" from which springs may issue (r), whilst at the coast (s) it could cause artesian flows from coastal wells (t) or from fractures out to sea (u). For every foot of fresh water above sea level there is theoretically 40 ft of fresh water below an island before salt water is eventually reached (v), although in practice a zone of mixing (w) occurs above the salt water. Salt water may be drawn towards the surface and pumped from wells in which the pump suction is below sea level (x).

the sea and emerges at the coast at sea level as springs.

Ground water will be available readily from the Mulifanua rocks, and the scoriaceous nature of part of the flows ensures that the quantities can be large. However, the upward rise of the water table from the coast is expected to be at a very low gradient (say 1–4 ft per mile) and wells would have to be sunk almost to sea level to obtain water.

Lefaga, Puapua, and Aopo Volcanics

The water supply characteristics of the Lefaga, Puapua, and Aopo Volcanics differ from those of the Mulifanua only in that water obtained from the younger of them may have a high iron content. The areas covered by these rocks have at present the poorest supplies in Samoa, except where there is only a thin cover on older rocks (e.g., at Sili in Savai'i, where the Lata River flows over Puapua flows).

Vini Tuff

A surface stream, starting as a spring about 15 ft above sea level, flows outwards from the centre of Apolima. This never fails. On other islands of Vini Tuff there is no certainty of non-brackish supply, and roof catchment would undoubtedly be the ideal. As a stand-by, wells put down to sea level, as far inland as possible, should get the least brackish water available, and possibly even fresh water.

Sedimentary Deposits

Water should be available in shallow wells sunk in all sedimentary deposits except the highest Lalomauga Alluvium (where it would be available in deep wells). The quantity of water available would depend upon the size of the smallest individual fragments of the deposit (e.g., gravels would give the highest yield, sands intermediate, and clays and muds the least). Where the well is near the coast, brackish water is liable to be encountered, at least at low tide.

Although the sheet-flood alluvium has been omitted from the geological maps for clarity, its presence has an important bearing on some water supply problems. The silt brought down by past floods and spread over much of the surface of young flows may have choked the cracks and fissures to such an extent as to limit the water available from shallow wells. In such cases deep wells could still obtain a worthwhile supply, and the water would still rise to the level it would have occupied had no silt been deposited.

CHAPTER 7—PRESENT AND FUTURE SUPPLIES

Present Supply Position

Introduction

The fieldwork on which this bulletin is based was carried out in the last two and a half months of the dry season – which, in 1956, was drier than usual. As a result, conditions were seen at their worst. The "present supply position" as shown on the hydrological maps (maps 1H and 2H) is based solely upon these observations, and must be considered as typical of conditions at the end of a prolonged dry spell.

In the summary of the present position that follows, both islands have been divided into three broad areas.

Upolu

NORTHERN AND WESTERN COASTAL UPOLU

Villages in northern and western coastal Upolu are relatively well supplied with water. The pipelines running west from Apia (with several supply points) and north from Falelatai, provide for many villages; and although more water could beneficially be supplied to their distant ends, both work well. The other villages are supplied by coastal springs or wells and their supplies vary from good to poor.

SOUTH COAST UPOLU

The south coast area of Upolu is moderately well supplied with water. One small pipeline exists at Safa'atoa, and some rivers and springs are adequate at present. There are still a number of villages with inadequate supplies, however, the usual defect being that the drinking water is salty at high tide at least.

EASTERN UPOLU

Eastern Upolu has the worst water supply of the three broad areas of that island; but is not bad by some Savai'i standards, and only slightly worse than South Coast, Upolu. Two very small pipe schemes operate, but apart from these, a few villages have good supplies. More than half the villages, however, especially in Aleipata, rely upon poor water that has been carried some distance. The two worst defects are complete lack of water or a salty supply from coastal springs.

Savai'i

SOUTH-EAST AND EAST SAVAI'I

Apart from those on the well operated Palauli schemes, only four villages have adequate supplies of fresh water in south-east and east Savai'i. One of these (Tafua) is two miles distant, a second (Asaga) is reached by track or canoe, a third (Tuasivi) uses rainwater, and a fourth uses a well. The most common defects in the other villages is that the water is scant or is salty at high tide. Water carriers may walk literally miles for drinking water, and even then must often make their journeys correspond with low tide to obtain fresh water. Many churches have tanks supplied from a small area of their roofs, but no tank contained water at the end of the dry season.

The Palauli pipe scheme was only just receiving sufficient water, and the pipe cannot be extended.

NORTHERN SAVAI'I

The northern part of Savai'i is the best supplied with water, and reaches the standard of southern Upolu. Three pipe schemes operate – those at Patamea and Paia work well, although the former has only just sufficient water and could not be extended. The Fagamalo pipe is supplied from a broken dam in the Vaipouli River, but the villages furthest east of Fagamalo (e.g., Saleaula) receive water only during the night. West of this scheme the villages rely upon good or bad coastal springs and wells.

WESTERN SAVAI'I

Western Savai'i has the poorest water supply in Western Samoa. Two villages have a good water supply – one (Sala'ilua) having a piped supply, and the other (Taga) being like an oasis at the western end of the south coast. The Sala'ilua piped supply provides only sufficient water for the one village in the dry season. All other villages in this area rely upon poor coastal springs, leaking tanks, salty or dirty wells, or even upon rain pools for their supplies.

Future Requirements

Quantity

The quantity of water required for any scheme can be readily calculated if the present population of the area, the rate of increase, the period for which the scheme is planned, and the consumption per head per day are all known. Only the last is relevant for discussion in this bulletin.

The daily consumption of water per head of population varies widely with country, with local conditions of industry and agriculture, and with the availability of water. In New Zealand the consumption ranges from about 25 gallons per day in rural communities to 80 gallons per day in cities where industry requirements are substantial. Schofield (1959) assumed that at Niue Island 20 gallons per head per day would be sufficient for some time to come. In Aleipata (Upolu), where water was obtained from some distance by the bucketful, rough measurements suggested that six bucketfuls per family per day (about one gallon per head per day) was actually being used.

It is likely that consumption at Samoa will eventually tend to become steady near to the New Zealand rural figure of 25 gallons per head per day. In the intervening period, however, the figure will vary widely from a few gallons a day where water is short, up to possibly as much as 40 gallons a day where water is plentifully supplied by pipe.

Quality of Water

Only three factors are likely to affect adversely the quality of Samoan water supplies: (1) bacteriological content; (2) high iron content; and (3) high salinity. Provision already exists in the Health Department for carrying out bacteriological tests. An adverse high iron content is likely only with waters from Puapua or younger flows, and there is as yet no record of water having been condemned on this account. High salinity, on the other hand, makes many springs useless at high tide at present, and salinity tests will be necessary in the sinking of wells close to sea level to ensure that shotholes put down ahead of sinking do not let saline water into the well. If it is found that they do, they should be plugged and further sinking abandoned. For this work a field kit-set for testing for salinity would be desirable.

Rainfall Records

Additional rainfall-recording stations are necessary to forecast better the installation of rainwater schemes. These records are needed especially from those parts of both islands where other forms of supply will be limited or costly (e.g., especially the higher country) and where development is likely to proceed in the next few years. It is important that the records indicate the distribution of rainfall throughout the year as well as the annual total.

Stream and Spring Gauging

Should any scheme be proposed that involves the use of stream or spring water, it is essential that data concerning the maximum and minimum flows should be available that cover a period of several years. It is therefore necessary that all of the larger streams and springs be gauged regularly, with especial attention to times of high flood and of low flow.

Ground-water Gradient

As more wells are sunk in Samoa, ground-water gradients should be carefully determined. Only one measurement of gradient has been possible so far: slightly less than 1 ft 6 in. per mile at Afia where the surface rocks are Mulifanua Volcanics.

Recommended Future Supplies

Introduction

The hydrological maps (1H and 2H) include a summary of recommendations as to the future supplies of water for different areas of the Territory. The numbers on the maps refer to the individual schemes or well sites as they are numbered in the detailed description that follows here. The urgency of each scheme is indicated by the letters A (most urgent) to D (least urgent). The degree of urgency was based initially upon a comparison of dry season supplies to the different areas. Several amendments to this simple classification were required, however, in order that the techniques of supply required for one area might be attempted initially in a less complicated area. The cost of the schemes has not been estimated, but economic considerations could influence the order in which the schemes are implemented.

Only four schemes are placed in the most urgent category (A). Each one of these involves the use of techniques that are either unknown, or are poorly known, in Samoa – the efficient use of rainwater, the pumping of spring water, the sinking of a deep well as at Afia, and the drilling of a deep well. They are the first four schemes to be considered.

Many schemes involve wells, but little is yet known about Samoan ground-water conditions. The recommendations are therefore based upon a combination of this knowledge, small though it is, and the experience of other Pacific islands. After a few deep wells have been put down in

Samoa, additional invaluable information will be available. The recommendations should then be reviewed. If yields are far lower than the Afia well indicates, more wells, closer together, would be necessary; if drilling proved easy and economic, it might be worth while siting holes somewhat higher, building reservoirs alongside them, and reticulating the water from there; or if ground-water gradients were steeper than has been presumed, drilling could be extended further into the high country.

For the above reasons accurate sites cannot be given for the wells, and those shown on the maps must be considered as approximate only. Precise sites will have to be selected later for each scheme in turn. It is desirable for drilled wells, and essential for dug wells, to be landwards of any source of bad surface pollution. Provided they cannot be polluted, there is no objection to their being in a hollow to decrease their depth. In all cases the surface height above sea level should be known so that adequate precautions can be taken against the possible pumping of sea water should drilling or sinking below sea level be required.

The assumption has been made throughout that both diesel generating sets (to drive submersible centrifugal pumps) and drilling rigs will be available. If they are not available, sites will have to be shifted appropriately seawards, if that is possible, in order to reduce the depth of the well.

Short-term Improvements

In the detailed descriptions that follow, a relatively long-term view is taken of water supplies. Clearly there must be a gap of many years before some schemes can be implemented. It may well be desirable, therefore, that short-term improvements be made to the water supplies of some villages. As a general rule, roof catchment schemes are most suitable here, especially where the rudiments of the installation already exists. Shallow wells would also provide cheap and rapid relief for some coastal villages. Such wells should be started preferably not more than 10 ft above sea level.

Schemes Depending on Rainwater

1. A'OPO (North Central Savai'i; Urgency A)

Little need be added to the data given above on rainwater supplies, beyond re-emphasising that for many places like A'opo, and also in much of the higher country, roof catchment is likely to be the only feasible and economic source of supply. Its utilisation involves techniques that are relatively simple, but the solution of its problems are just as important as the solution of any other problems connected with Western Samoan water supply.

Schemes Depending on Pumping of Springs

2. NORTH FA'ASALELEAGA (Asaga Spring, East Savai'i; Urgency A)

At Asaga, in North Fa'asaleleaga, a large spring emerges at the head of a large stream, very close to sea level, but at some distance inland. The stream is tidal up to the spring, but at low tide the whole stream (many yards wide and several feet deep) is composed of fresh water. The flow of this stream is unknown but clearly large. Asaga village gets its supplies of drinking water from this spring, and also uses it for bathing, with the help of crude concrete walls that partly baffle out the salt water. A properly designed intake structure would probably allow water to be pumped from this spring throughout the tidal range. This, together with a suitable reservoir, should supply ample water for the villages from Pu'apu'a to Tuasivi, and possibly even south of the latter into south Fa'asaleleaga.

There are two important features in this scheme. Firstly, most existing water schemes are gravity fed, but inevitably there is a limit to the water that is available from such sources. Sooner or later pumps will be required in many parts of Samoa, and experience in their use is desirable. Secondly, water from coastal springs could make an important contribution to overall Samoan supply. It is important to find how this source will work in practice. Asaga Spring has probably the best flow and is the most likely to be pumpable at all tides. Salinity and flow tests are essential prior to the installation of all such schemes, and the former are desirable during installation.

Schemes Depending on Wells

3. FALEALUPO (North-west Savai'i; Urgency A)

The villages from Papa around the Falealupo Peninsula coast to Falelima are all poorly supplied with water. A single reservoir, sited at about the centre of the base of the peninsula (i.e., say where the Falealupo road leaves the Sataua–Falelima road), would supply all this area. The reservoir would best be supplied with water from a hole to ground water beside it. Although the ground-water gradient is unknown here, it is assumed to be low, and the depth of the hole would probably be no less than 400 ft. Thus a diesel generator set might be needed for the pump, and a drilled rather than a dug well is indicated. Conditions here are good for commencing a drilling programme in Western Samoa. The well site could be close to the road, giving good access, water for the water truck would be available at Sataua (under 3 miles), and the drill would encounter rather more scoriaceous rock than the average for Samoa, which would lead to easier drilling.

One of the essential features of such a project would be an accurate determination of the height of the site above sea level prior to commencement, so that the drillhole could be test-pumped at sea level if the quantity of water were in doubt. Subsequent drilling would need to proceed cautiously with regular tests for salinity.

It is recommended that a drillhole be put down. If for some reason a drill were not taken to Samoa, or if the provision of a diesel generator set were unacceptable, a well should be sunk on the Falealupo road at 150–200 ft above sea level, with a more limited area for reticulation.

4. South Fa'asaleleaga (East Savai'i; Urgency A)

The area of South Fa'asaleleaga, from Tuasivi south to Salelologa, would best be supplied from a single deep well. The ideal site for this would be near the 'Eve'eve – Vaiola track close to the boundary between Salani and Mulifanua rocks. At this point the ground surface is about 200 ft above sea level, and hence 200 ft would be the maximum depth of the well. However, since the Salani rocks are well weathered locally, the ground-water gradient may be steeper than is usual, and it may be unnecessary to sink the well as far down as sea level to obtain water. At the same time the weathering would imply a reduced yield compared with the Afia well; but it should still be large by normal standards.

A volcanic cone is conveniently situated nearby for building a reservoir whence the water could be reticulated to the coast.

Wells such as this could be sunk anywhere in Samoa, with Samoan labour (witness the Afia well), provided that the depth were not too great.

5, 6, and 7. Letui-Safune-Safotu (North Savai'i; Urgency B, C, and D)

Letui village, 250–300 ft above sea level, is at present without water. A well there would supply not only its needs, but could feed water into a coastal pipeline to supply the villages between Sasina and Safune. It is becoming normal practice in Samoa for these coastal pipelines to be joined, and presumably the Safune and Safotu areas would eventually be so joined. Safotu has three possible sources of water. Its present needs could probably be supplied by a piped scheme from the stream that already supplies Paia with piped water and is to the east of that village (370 ft above sea level). However, there is insufficient water available for any extension beyond Safotu, or for future development. Coastal wells west of Safotu could be harnessed if Scheme 2 at Asaga proved successful. The best source of supply, however, is probably a well between Paia and the hills to the east. This would again be about 300 ft above sea level.

A third well might be necessary to supply the Letui-Safune-Safotu area. If so it would best be sited at some suitable point below the road up to Ologogo (Wetzell's) Plantation.

8 and 9. West Coast, Savai'i (Fagafau and Sala'ilua; Urgency B)

The reservoir at Sala'ilua has sufficient water to supply much of western Savai'i during the wet season, although during the dry season it requires supplementing. Undoubtedly the best source for this additional water would be from a well alongside the reservoir (i.e., about 700 ft above sea level). Additional roading would be needed to take in a rig. In view of the weathered nature of the rocks immediately east of the present spring source, it should not be necessary to drill to sea level to reach the water table.

Additional water must also be fed into the north-western end of this western Savai'i pipeline. A well site inland from Fagafau or Samataiuta would be suitable from geological considerations provided that it were on Mulifanua rather than on Puapua rocks. However, no road extends inland here for use by a drilling rig, and it might be necessary to drill immediately landwards of one of the villages. In such a case, salinity tests would be essential.

10 and 11. Sataua-'Auala (North-west Savai'i; Urgency C)

The Sataua-'Auala area will need to be supplied from a well. An ideal site would be at the base of the steep rise (fault scarp) along K. Va'ai's road, about 2 miles inland and 500–550 ft above sea level. Alternatively, and essentially guided by drilling experience in Samoa up to that time, the site could be shifted to above the rise so that the upland country, potentially useful for raising cattle, could also be supplied.

To allow for future development, or to make up for any deficiencies in the supply of a single hole, a second hole might be desirable along the road towards A'opo at some suitable point. This point should be selected with Mulifanua rocks at the surface to reduce the possibilities of obtaining water highly charged with iron.

12. Inland Fa'asaleleaga (Eastern Central Savai'i; Urgency C)

Inland Fa'asaleleaga could be supplied by surface water from the upper Faleata River, but piping, over the considerable distance through undeveloped country, would present problems. Initially it might be advisable to use a well sited within the Salani rocks three to four miles inland. Such a hole would be 600–800 ft deep. Possible sites would be at Vaiola, Tapu'ele'ele, or at the end of the inland track from 'Iva. Access in every case would be difficult, and this might decide for Vaiola rather than for the 'Iva track, although the latter would be preferable from the point of view that it is further from the proposed well on the 'Eve'eve – Vaiola track.

The proposed well would probably reach the water table well above sea level.

13. SALE'AULA (North-east Savai'i; Urgency C)

A well inland from Sale'aula, sited in Mulifanua rocks, would be able to supply water to the eastern end of the Fagamalo pipeline, provided access were satisfactory.

14. TAGA (South-west Savai'i; Urgency D)

A great area between Sala'ilua and Sili-Gataivai is without water and therefore scarcely developed. It could be supplied from a well at the point where the Taga track turns southwards, but access at present would be difficult.

15 and 16. LEFAGA (South-western Upolu; Urgency B)

The large area covered by the very porous Lefaga Volcanics in south-western Upolu is poorly supplied with water, and surface water is not available. Here a well in Lefaga rocks close to their western contact with the Fagaloa Volcanics (see maps) should provide adequate water at not too great a depth. No site was prospected here, and clearly access will have a great deal to do with the siting of the hole. The site indicated on map 2H could be changed markedly without detriment. There is no point in being closer than, say, 200 yards to the Fagaloa Volcanics.

A second well will probably be required to the east of this area, say inland from Sa'anapu.

17 and 18. VAIALUA AND SALE'IMOA (Northern Upolu; Urgency B and C)

A good supply of water, fed into the western end of the Apia pipeline, would be of great value. Two wells are therefore recommended in this area. The first, half a mile inland from the coast at Vaialua (12 miles west of Apia) and 30 ft above sea level, would be experimental in part. It would aim at finding out how great a flow might be expected from wells that are shallow but that are sited well inland. The proposed site is away from villages and pig paddocks, although, being seawards of a plantation, it might need to be carefully protected against contamination. A shallow well already exists a few hundred yards on the seaward side of the site, beside a European house. This well is 7 ft deep, and contains 4 ft of water, which is not salty and is not affected by tidal fluctuations. Judging by experience at Afia well, this water must be perched. Unless a large volume of water is obtained earlier, the proposed well should be sunk to sea level, or even below with careful salinity tests. The pump intake should not be set below sea level.

The second well in this area would be deeper, and should be sited in or near the plantations south of Sale'imoa, 1–1½ miles inland and 100–200 ft above sea level (i.e., a similar position to Afia well to produce, it is hoped, a similar supply).

19 and 20. SATAPUALA AND MULIFANUA (North-west Upolu; Urgency B and C)

Similar wells to the deep one proposed inland from Sale'imoa, should be sited inland from the western part of Satapuala and south-west of Mulifanua. These two wells should enable a connection between the Apia pipeline and that from Falelatai, feeding in the necessary additional water at their distant ends.

21 and 22. WESTERN UPLANDS (Upolu, Near Cross-island Road; Urgency C and D)

One deep well (say commencing at least 500 ft above sea level) is proposed on the northern side of the cross-island road. It might be unnecessary if others in this area (17, 18, and 19) are high producing; but if they are not this would not only yield valuable additional water to the main pipe and to local land development but would give useful and necessary data regarding the deeper wells.

Regardless of whether or not the above well is put down, a well is strongly recommended near the summit of the island to provide water to the upland cattle area. To have a reasonable chance of obtaining water at other than close to sea level, the hole should be sited close to the hills of Fagaloa rocks to the west of the cross-island road (see Map 2). Possible holes to the east could be put down according to the success of this first deep hole, but the water table would be probably considerably deeper in them.

Schemes Using Surface Water and Inland Springs

23. TAFUA (South-east Savai'i; Urgency B)

The replacement of the existing pipe, and the siting of an intake wall about 30 ft downstream is urgently required. Precautions against water-hammer in the pipe may be necessary if only a few taps are fitted.

24. SILI-PALAULI (Using Lata River, South Savai'i; Urgency C)

The flow of the Lata River at Sili village is clearly very large. Further upstream the Tapuafea Fall (50 ft) may be an excellent source of water for the Sili-Gataivai area and for pipelines in many directions therefrom. Careful observations, but without flow meters, suggested that the flow at this fall was 10 times greater than that at the Palauli pipe-scheme intake. Further investigations, however, might show pumping to be necessary.

25. PUNA-PATAMEA (Puna Spring; Urgency D)

Puna Spring, inland from Patamea, is reputedly a good source of water, which, if round-the-year gaugings show sufficient water, could be added to the existing Patamea pipeline. The latter could then be extended from Samalae'ulu to supply the Solomea-Papalaulelei area.

26. UPPER VANU TO FALEATA RIVERS (South Savai'i; Urgency D)

The Vanu River flows in the base of the deepest gorge in southern Savai'i, but contains water only above Asolelei (old village) in the dry season, and is useless except to water the immediate area. Other tributaries, however, contain useful water. The Tiapua River at the point where the track to Asolelei crosses it, has twice the flow of the Faleata River at the Palauli pipe-scheme intake, and could be used (with pumps) to supply water to the surrounding area. The Lata and Faleata Rivers, and some of their tributaries, have ample water in their upper parts to supply water to the land on either side, and development in these areas might well be able to proceed early by virtue of this fact. The upper reaches of the Faleata River, downstream from Fusi Swamp, for example, were once considered as a possible source of water for Fa'asaleleaga. The water could well be used for supplying the nearby land.

27. ALEIPATA (Using Mulivai, or Ti'avea, River, Eastern Upolu; Urgency B)

"Richardsons Track" crosses the headwaters of the Mulivai River at 1,025 ft above sea level, about 3 miles west-south-west of Ti'avea. The flow at this point, a little downstream from springs, is small, but might be usefully developed. A little over half a mile downstream, the surface water from the impermeable Fagaloa country to the north has joined that from the more permeable Salani country to the south, and the flow of the river is estimated at 10–20 times greater in a series of low falls. Clearly, sufficient water exists here to supply Aleipata for some time, but the engineering problems are greater than the upstream position since the pipeline would have to be strung across a deep gully. The project is not impossible, however, even if pumps are needed in the last resort; but no project should include open channelways relying upon rock floors. Even under natural conditions dry gullies exist at a lower level close to the main stream, owing to perching of the latter on a basalt flow.

28. SALANI (Using Fagataloa, or Salani, River, South-east Upolu; Urgency B)

The harnessing of the Fagataloa (Salani) River will be a major project in Samoa.

The four main falls should be capable of development in either hydro-electric (see p. 63) or water-supply schemes, or both. Minor falls in the river could supply water via ram pumps to the nearby areas. There is little doubt that water from the Fagataloa River will eventually be piped to the south coastal area from Lepa to Poutasi, and possibly beyond, as well as to the higher country closer to its valley.

29. SOUTH CENTRAL UPOLU (Using Mataloa and Mulivai Rivers; Urgency C)

Water from the Lefaga scheme (15 and 16) should supply villages as far east as Lotofaga, and that from the Fagataloa scheme (28) should supply those as far west as Poutasi. The area between Lotofaga and Poutasi might also obtain water from these sources, but more local supplies would be desirable for stand-by purposes, if nothing else. A waterfall on the Mataloa River, near the Agriculture Department's house sites, carries a good volume of water. With suitable health precautions a good supply could be obtained from there, or from further upstream.

At the lower site, at least, pumping might be necessary, but so it would from any alternative site using ground water, and there is the advantage that departmental officers could be in attendance. Some such scheme might even be put into operation quickly to supply piped water to the Poutasi area before water reaches there from Fagataloa River development.

W. G. McKay (lately Director of Public Works, Western Samoa) in an unpublished report quoted 250,000 gallons per day as the minimum flow (over a 5-year period) of the Mulivai River at a point which is taken to be 290 ft above sea level.

Should wells be needed in addition to these river supplies in the south coastal region, they should preferably be sited on Salani rocks, half to two miles inland.

30. FALEFA (North Upolu; Urgency D)

Development of the valley of Falefa Stream and its tributaries, especially in the direction of the Tavalagi Saddle to Aleipata, has already proceeded. These villages would be best supplied with water from intake weirs on streams and springs near the road about half a mile north of Tavalagi Saddle, or from an intake in the west branch of Falefa Stream.

The Falefa River, near its falls, would be a possible source for water for the coastal area to the west; but this scheme would probably require pumping and would almost certainly require a treatment plant.

31. FAGALOA (North-east Upolu; Urgency D)

In the wide region around Fagaloa Bay, the Fagaloa rocks carry numerous small surface streams. Here water-supply problems concern very small areas, and should be easily solved by the use of surface water.

32. APIA PIPELINE (North Upolu; Urgency D)

Additional water could be made available to the Apia pipeline when the Alaoa hydro-electricity scheme is completed. Similarly, additional water would be available if at some future date hydro-electric power were to be used from the upper Soaga River. Proposals have been given above (Nos. 17 and 18) for the addition of well water to the pipe.

Other Areas

33. SMALLER ISLANDS (Apolima and Manono; Urgency D and C)

Of the smaller islands, only Apolima and Manono are populated.

Apolima has a good supply from a spring, and piped water could be obtained by pumping from this. Additional water would be available from roof catchment or from a shallow well further inland than the spring. Water should be found here 15–30 ft above sea level.

Manono has only a few springs, and they are brackish (Thomson, 1921, p. 59). The best permanent water supply would probably be from a drillhole as far from the coast as possible (to avoid saline contamination). In the meantime roof catchment is recommended.

34. CENTRAL UPLANDS (Both Islands; Urgency D)

So little is known for certain regarding water supply sources in Samoa that several of the above recommendations may have to be modified in the light of the experience gained in implementing the earlier ones. In view of this there is little point in making specific recommendations for the higher central uplands of either Upolu or Savai'i. Rain-water catchment seems likely to be the most important supplement to the use of the meagre surface-water supplies. Drilling experience may show, however, that ground water is likely to be available in some localities, especially near outcrops of the Fagaloa and older Salani rocks.

APPENDIX

LIST OF THIN SECTIONS EXAMINED BY DR R. N. BROTHERS

FAGALOA VOLCANICS

Locality Number	Thin Section	Rock Type	Locality
Upolu Island			
523	16624(1)	Trachyte ..	.. Dam below Alaoa power station
525	16626(1)	Olivine basalt	.. Old road cutting above Alaoa power station
	16626(2)	Harzburgite ..	.. Nodule in lava; old road cutting above Alaoa power station
526	16627(1)	Olivine basalt	.. Afulilo Falls, upper Vaigafa R.
	16627(2)	Olivine basalt	.. Afulilo Falls, upper Vaigafa R.
	16627(3)	Feldspathic basalt	.. Afulilo Falls, upper Vaigafa R.
527	16628	Olivine basalt	.. Ridge north of Afulilo Falls
528	16629(1)	Aphyric basalt	.. Track up east side Mt. Vaea
	16629(2)	Olivine basalt	.. Track up east side Mt. Vaea
529	16630	Olivine basalt	.. On Falefa Rd. below new Fagaloa Rd.
530	16631	Hornblende andesite	.. New road to Fagaloa Saddle.
531	16632(1)	Olivine dolerite	.. Soaga R., half way to Falls
	16632(2)	Olivine dolerite	.. Soaga R., half way to Falls
532	16633(1)	Vitric tuff ..	.. Soaga Falls
	16633(2)	Olivine basalt	.. Soaga Falls
533	16634	Olivine basalt	.. Higher quarry above Ti'avea village
Savai'i Island			
616	16655(1)	Picrite basalt ..	.. Gravel in Vanu R.
	16655(2)	Anorthoclase trachyte	.. Gravel in Vanu R.
	16655(3)	Picrite basalt ..	.. Gravel in Vanu R.
	16655(4)	Picrite basalt ..	.. Gravel in Vanu R.

SALANI VOLCANICS

Locality Number	Thin Section	Rock Type	Locality
Upolu Island			
508	16609	Olivine basalt	.. Top of escarpment above Soaga Falls
509	16610	Olivine basalt	.. Track above Ti'avea
510	16611	Olivine basalt	.. Taimasa cone, half mile inland, Aleipata
511	16612(1)	Olivine basalt	.. Samusu, Aleipata district
	16612(2)	Analcite basalt	.. Samusu, Aleipata district
	16612(3)	Picrite basalt ..	.. Samusu, Aleipata district
512	16613(1)	Picrite basalt ..	.. Tuialemu rock fall
	16613(2)	Picrite basalt ..	.. Tuialemu rock fall
513	16614	Picrite basalt ..	.. Flat above Ti'avea village
515	16616(1)	Olivine basalt	.. Olomauga, Aleipata district
	16616(2)	Olivine basalt	.. Olomauga, Aleipata district.
516	16617(1)	Olivine basalt	.. Sopo'aga Falls, Vaiau's Farm
	16617(2)	Olivine basalt	.. Sopo'aga Falls, Vaiau's Farm
524	16625(1)	Olivine basalt	.. Sopo'aga Falls, Vaiau's Farm
	16625(2)	Olivine dolerite	.. Sopo'aga Falls, Vaiau's Farm
536	16637	Olivine basalt	.. Waterfall, upper Ti'avea River
Savai'i Island			
606	16645	Analcite basalt	.. Plateau above Lata River
607	16646(1)	Olivine dolerite	.. Masania, old village, Lata River
	16646(2)	Analcite basalt	.. Masania, old village, Lata River
608	16647	Olivine dolerite	.. Legend stone, 1 mile NW of Sili
609	16648	Olivine basalt	.. Southern track to Vaiola, beside creek

MULIFANUA VOLCANICS

Locality Number	Thin Section	Rock Type	Locality
Upolu Island			
501	16602	Olivine dolerite	.. Point on coast, near "Chief's Tomb", Falelatai
502	16603	Olivine dolerite	.. East end of Satapuala airstrip
503	16604	Olivine dolerite	.. Road cutting, Samatau village
504	16605(1)	Analcite basalt	.. Centre inland of Falefa flow
	16605(2)	Analcite basalt	.. Centre inland of Felefa flow

MULIFANUA VOLCANICS—*continued*

Locality Number	Thin Section	Rock Type		Locality
Savai'i Island				
610	16649	Olivine basalt	..	West corner Asau Bay
611	16650	Olivine basalt	..	Banana plantation, 3,300 ft above A'opo
612	16651(1)	Olivine basalt	..	Cliff section, Papa village
	16651(2)	Olivine basalt	..	Cliff section, Papa village
613	16652	Olivine basalt	..	Headland east of Sataua village
614	16653	Olivine basalt	..	Headland east of Sataua village
615	16654	Olivine dolerite	..	Coast, in bay between Satupa'itea and Fa'ala

LEFAGA VOLCANICS

Locality Number	Thin Section	Rock Type		Locality
Upolu Island				
506	16607(1)	Olivine dolerite	..	Road to Lotofaga, below Sopo'aga Falls
	16607(2)	Olivine dolerite	..	Road to Lotofaga, below Sopo'aga Falls
507	16608	Olivine dolerite	..	Pit on roadside to Lotofaga
517	16618	Picrite basalt ..	..	Coast at Tafagamanu
518	16619(1)	Picrite basalt ..	..	Safa'atoa quarry, on northern road across island
	16619(2)	Picrite basalt ..	..	Safa'atoa quarry
537	16638	Picrite basalt ..	..	Lotofaga village, west of Vaie'e Peninsula, south coast

PUAPUA VOLCANICS

Locality Number	Thin Section	Rock Type		Locality
Upolu Island				
500	16601(1)	Picrite basalt ..	..	Beach and platform west of 'Ili'ili village
	16601(2)	Vitrophyric basalt	..	Beach and platform west of 'Ili'ili village
523	16624(2)	Limburgitic basalt	..	Dam below Alaoa power station
Savai'i Island				
600	16639(1)	Vitric tuff ..	..	Tafua savai'i, south cone slopes and coast
	16639(2)	Vitric tuff ..	..	Tafua savai'i, south cone slopes and coast
	16639(3)	Vitric tuff ..	..	Tafua savai'i, south cone slopes and coast
601	16640	Olivine basalt	..	Tafua savai'i, coast cliffs, east of village
603	16642(2)	Picrite basalt ..	..	One mile east of A'opo, on Asau track
	16642(3)	Olivine basalt	..	One mile east of A'opo, on Asau track
604	16643	Olivine basalt	..	Gataivai Spring

VINI TUFF

Locality Number	Thin Section	Rock Type		Locality
519	16620	Vitric tuff ..	..	Nu'utele Is., 200 ft above sea level on west side
520	16621(1)	Olivine basalt	..	Fanuatapu Is., 20–30 ft above sea level
	16621(2)	Olivine basalt	..	Fanuatapu Is., 20–30 ft above sea level
521	16622	Vitric tuff ..	..	Nu'utele Is. at sea level
522	16623	Organic limestone	..	Cape Tapaga, 20 ft above sea level
617	16656(1)	Vitric tuff ..	..	East headland of Apolima
	16656(2)	Vitric tuff ..	..	East headland of Apolima
619	16658(1)	Vitric tuff ..	..	At shipping light, Apolima
	16658(2)	Olivine dolerite	..	At shipping light, Apolima

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INDEX

Corrections to Maps

Maps 1 and 1H Savai'i

(a) Spot height at Fogātuli (central west coast) should be 200′ not 2001′.
(b) Sand spit extending north-west from Aopo lava that fills lagoon at Sale'aula should be "R", not "T".
(c) Vini Tuff should be described in legend as vitric tuff, not palagonite tuff.

Maps 2 and 2H Upolu

(a) A small area, roughly 100 yards wide, and extending southward from Cape Sa'eiv'a to the Mulivai River mouth (towards eastern end of north coast), should be shown as "T" (Tafagamanu Sand) and coloured appropriately. Its boundary is shown. In a few other small areas, where the colour or overprint has been omitted, the symbol or lack of geological boundary indicates the surface formation.
(b) Vini Tuff should be described in legend as vitric tuff, not palagonite tuff.

Fig. 40.

For Saleleoga (SE Savai'i) read Salelologa.

R. E. OWEN, GOVERNMENT PRINTER, WELLINGTON, NEW ZEALAND—1959

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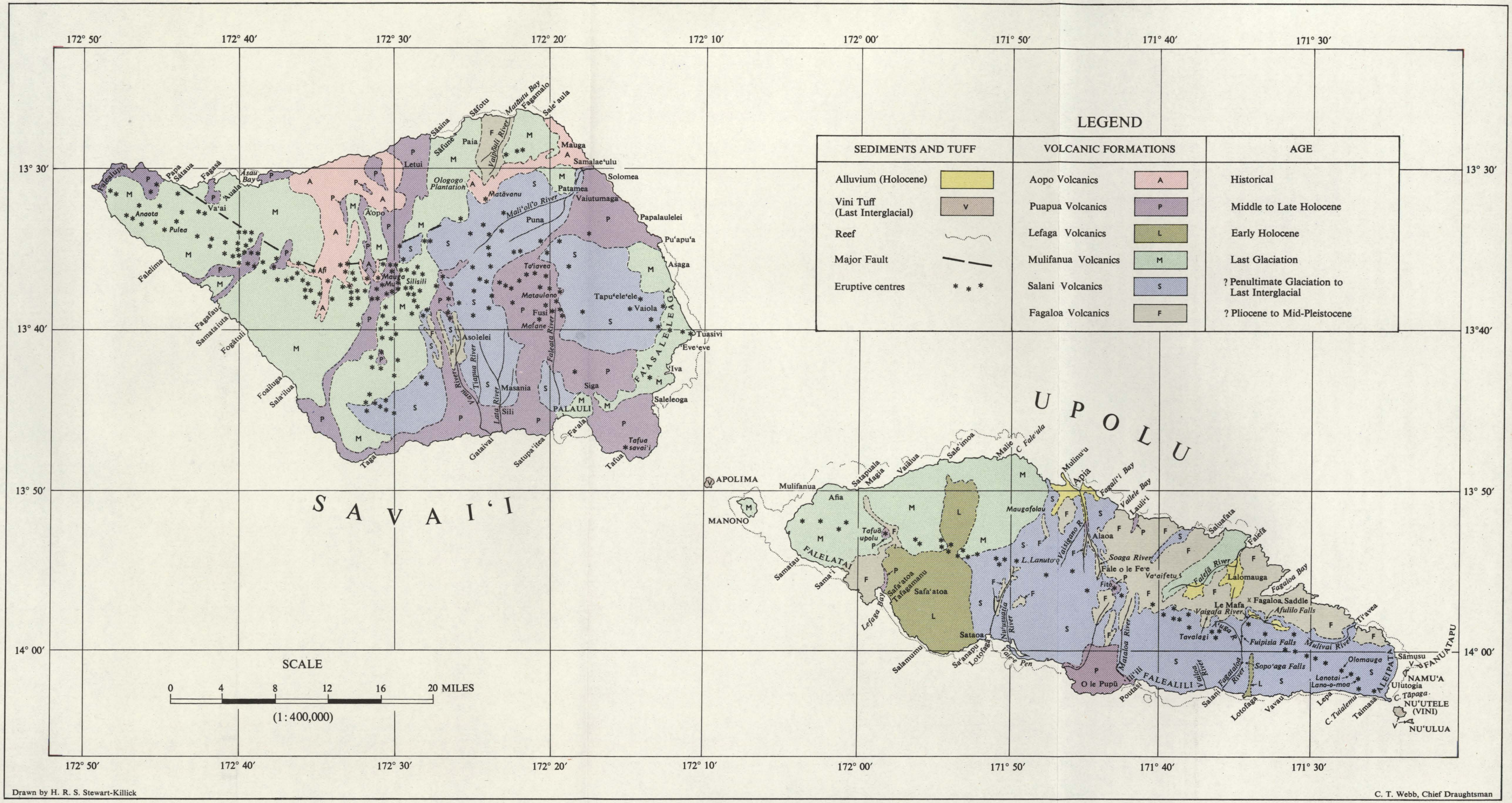


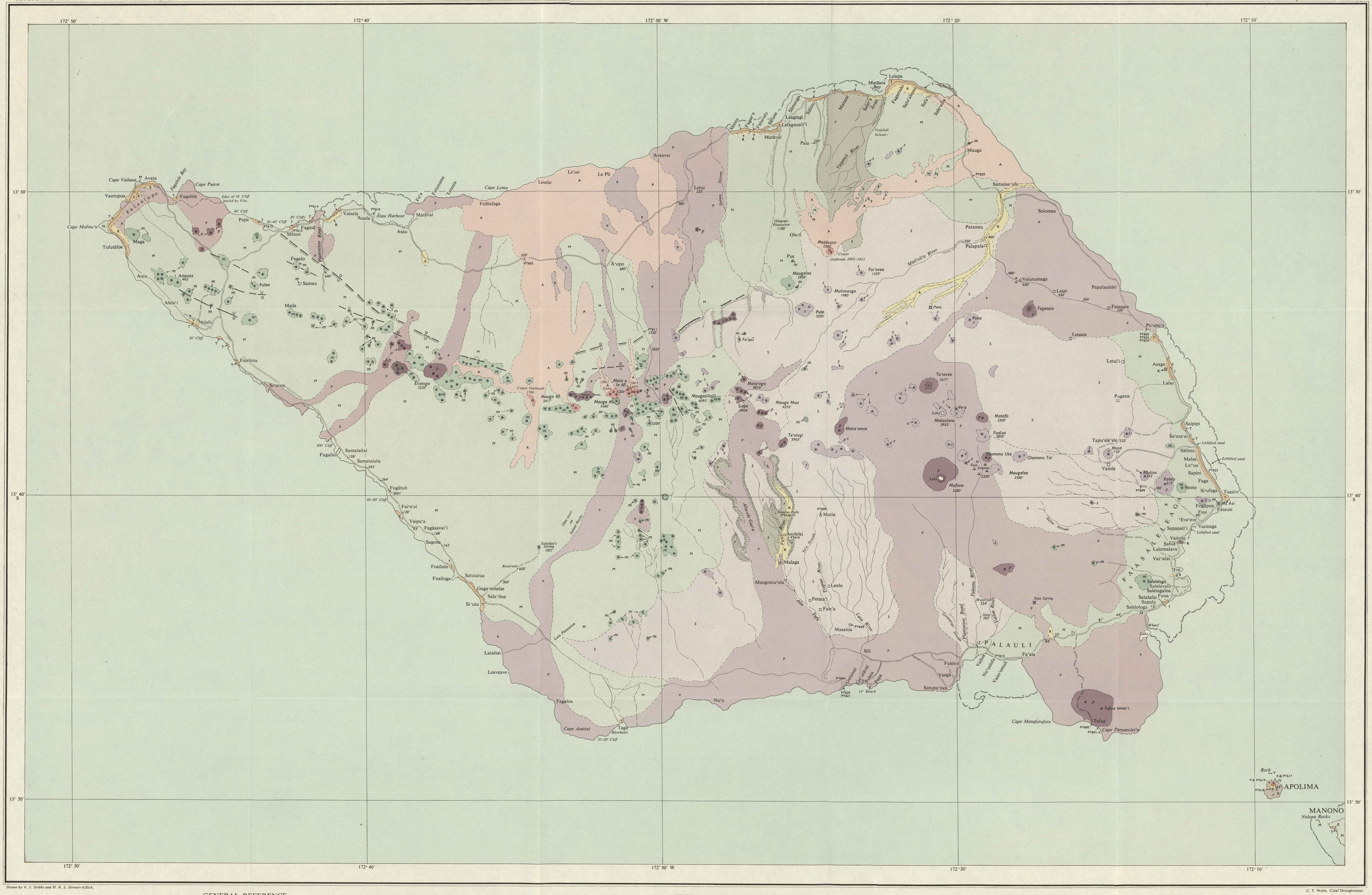
Fig. 40 Index map, showing the more important occurrences of the rock formations; the distribution of major cones; and the village, mountain, and river names that are mentioned in the text.

NEW ZEALAND GEOLOGICAL SURVEY

GEOLOGICAL MAP NO. 1 N.Z.G.S. BULLETIN NO. 63

SAVAI'I

1 : 100,000



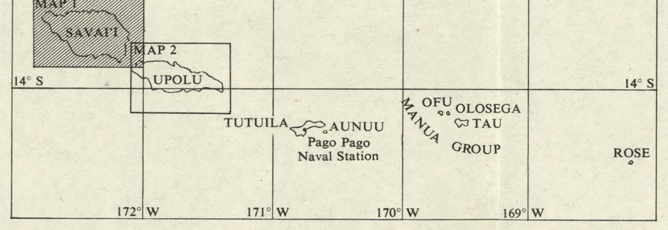
Drawn by V. J. Stobbs and H. R. S. Stewart-Killick.

C. T. Webb, Chief Draughtsman

GENERAL REFERENCE

- Geological boundary
- Faults
- Dip and Strike
- Escarpments, cliffs
- Centre of Eruption (commonly small crater)
- Inland Springs
- Coral reef
- Limits of prominent lava flow within volcanic formation
- Prominent swamps
- Roads (vehicular)
- Roads (non vehicular)
- Tracks
- Flowing Streams
- Stream channels
- Village — Vaitolo
- Village (abandoned) — Mutia
- Spot height in feet above Sea Level — 200'
- Petrological samples (locality and number) — PT620
- Phosphate samples — P612

INDEX TO ADJOINING SHEET



SCALE

1 : 100,000

0 1 2 3 4 5 MILES

R. W. Willett
Director

Compiled from data obtained from the Lands & Survey Department Apia Western Samoa
Additional Surveys and Geology by D. Kear, and B. L. Wood, New Zealand Geological Survey, and S. Poutoa, Public Works Department, Apia Some geological boundaries from soil survey of A. C. S. Wright, New Zealand Soil Bureau, 1956
Published by the Department of Scientific and Industrial Research 1958
R. E. Owen, Government Printer, Wellington, New Zealand

GEOLOGICAL LEGEND

	SEDIMENTARY ROCKS AND MARINE TUFF		VOLCANIC FORMATIONS		CONES
HOLOCENE	Alluvium Swamp talus etc. (including some Tafagamanu sand)	R	Aopo Volcanics (historical)	A	a
	Tafagamanu Sand (coastal strip of coral sand about 5 ft. above sea level)	T	Puapua Volcanics (reef-covering)	P	p
	Nu'utele Sand (coral sand 15 ft. above sea level)	N	* Lefaga Volcanics (narrow reefs offshore)	L	l
MIDDLE AND LATE PLEISTOCENE	* Lalomauga Alluvium (terrace gravels in Falefa Valley)	LA	Mulifanua Volcanics (wide reefs offshore)	M	m
	* Talus from Fagaloa Volcanics	Ft	Salani Volcanics (wide reefs, deep soils, canyons)	S	s
	Vini Tuff (palagonite tuff of eastern islands and Apolima Island)	V			
EARLY PLEISTOCENE OR PLIOCENE			Fagaloa Volcanics (steep eroded relief, deep soils, drowned coasts, narrow reefs)	F	

* None on this sheet

NEW ZEALAND GEOLOGICAL SURVEY

GEOLOGICAL MAP NO. 2 N.Z.G.S. BULLETIN NO. 63

UPOLU

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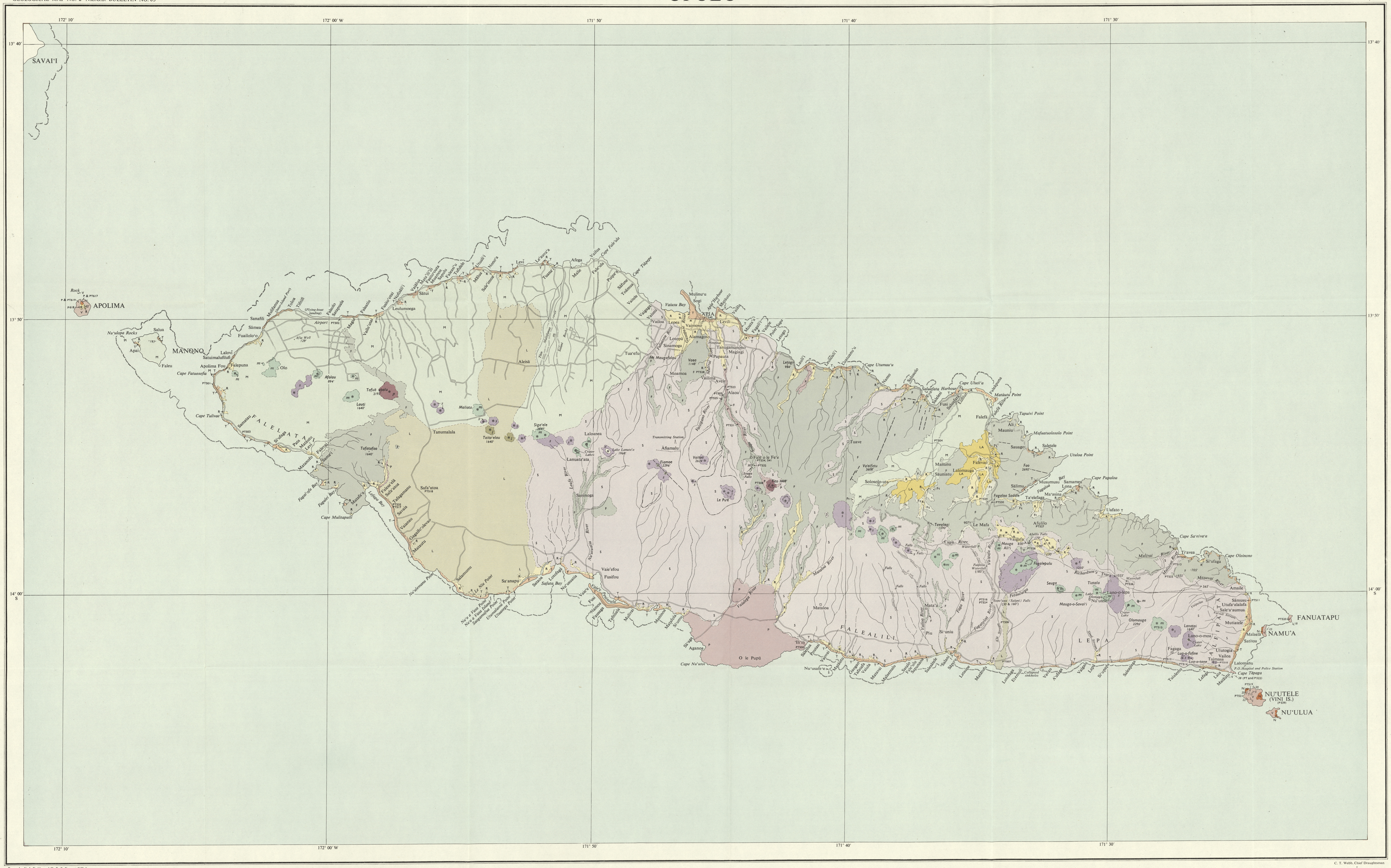


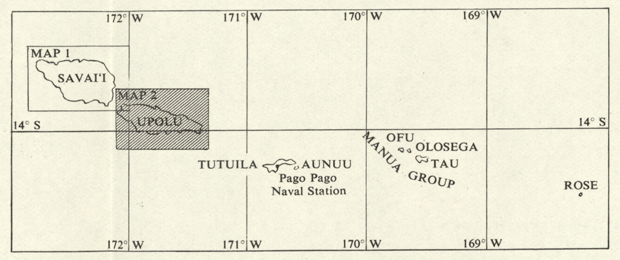
Drawn by V. J. Stobbs and H. R. S. Stewart-Killick.

C. T. Webb, Chief Draughtsman

GENERAL REFERENCE

- Geological boundary
- Faults (inferred only)
- Dip and Strike
- Escarpments, cliffs
- Centre of Eruption (commonly small crater)
- Inland Springs
- Coral reefs
- Limits of prominent lava flow within volcanic formation
- Prominent swamps
- Roads (vehicular)
- Roads (non vehicular)
- Tracks
- Flowing Streams
- Stream channels
- Village — Lataitai
- Village (abandoned) — Avele
- Spot height in feet above Sea Level — 480′
- Petrological samples (locality and number) — PT519
- Phosphate samples — P616

INDEX TO ADJOINING SHEET



SCALE

1 : 100,000

0 1 2 3 4 5 MILES

R. W. Willett
Director

Compiled from data obtained from the Lands & Survey Department Apia Western Samoa Additional Surveys and Geology by D. Kear, and B. L. Wood, New Zealand Geological Survey, and S. Poutoa, Public Works Department, Apia Some geological boundaries from soil survey of A. C. S. Wright, New Zealand Soil Bureau. 1956

Published by the Department of Scientific and Industrial Research 1958
R. E. Owen, Government Printer, Wellington, New Zealand

GEOLOGICAL LEGEND

SEDIMENTARY ROCKS AND MARINE TUFF

HOLOCENE	Alluvium Swamp talus etc. (including some Tafagamanu sand)	R
	Tafagamanu Sand (coastal strip of coral sand about 5 ft. above sea level)	T
	Nu'utele Sand (coral sand 15 ft. above sea level)	N
MIDDLE AND LATE PLEISTOCENE	Lalomauga Alluvium (terrace gravels in Falefa Valley)	LA
	Talus from Fagaloa Volcanics	Ft
	Vini Tuff (palagonite tuff of eastern islands and Apolima Island)	V
EARLY PLEISTOCENE OR PLIOCENE		

VOLCANIC FORMATIONS

		CONES
Aopo Volcanics (historical)	* A	a
Puapua Volcanics (reef-covering)	P	p
Lefaga Volcanics (narrow reefs offshore)	L	l
Mulifanua Volcanics (wide reefs offshore)	M	m
Salani Volcanics (wide reefs, deep soils, canyons)	S	s
Fagaloa Volcanics (steep eroded relief, deep soils, drowned coasts, narrow reefs)	F	

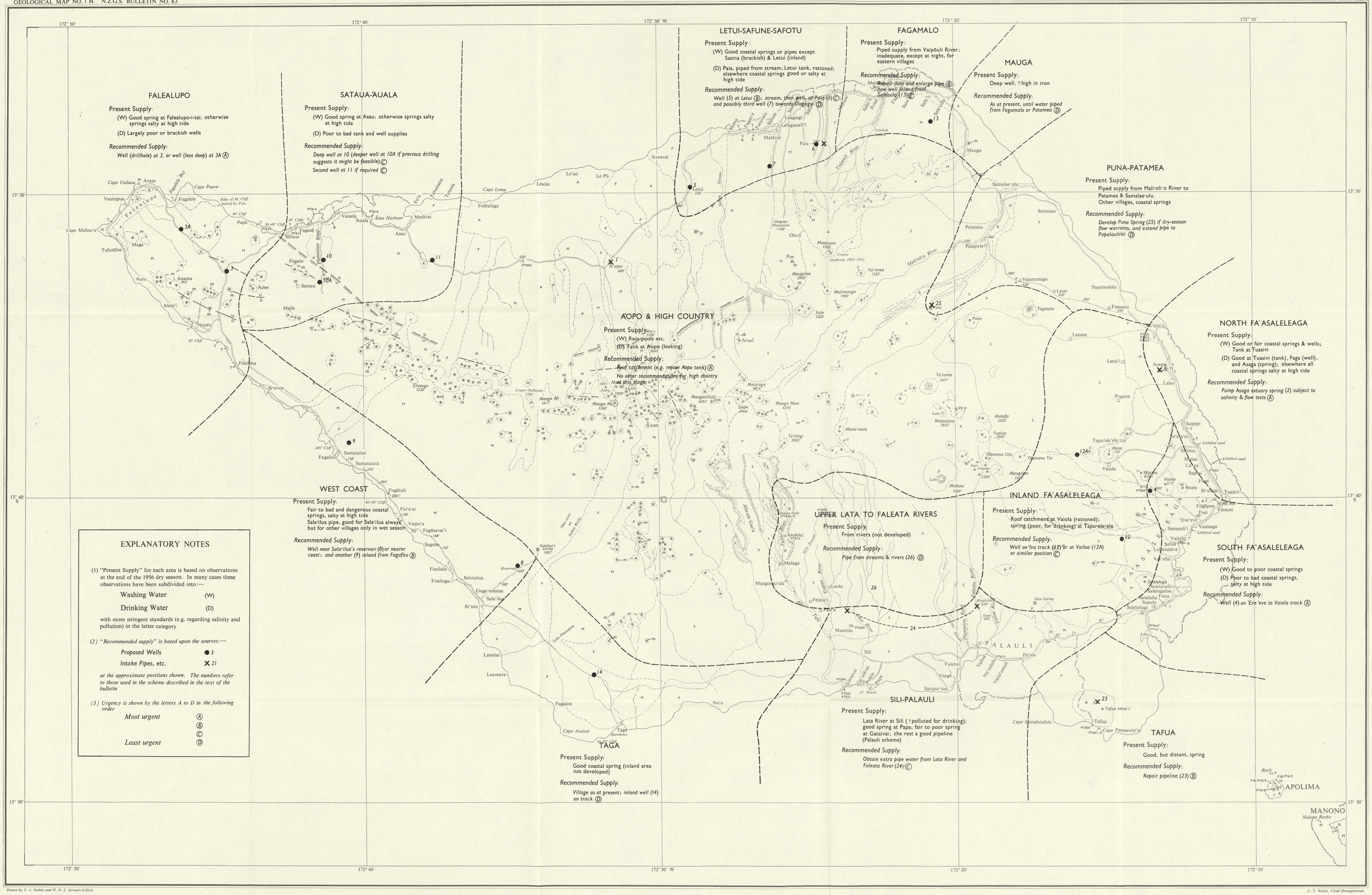
* None on this sheet

NEW ZEALAND GEOLOGICAL SURVEY

HYDROLOGY OF SAVAI'I

GEOLOGICAL MAP NO. 1 H. N.Z.G.S. BULLETIN NO. 63

1 : 100,000



Drawn by V. J. Stobbs and H. K. Stewart-Killick.

C. T. Webb, Chief Draughtsman

GENERAL REFERENCE

- Geological boundary
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- Centre of Eruption (commonly small crater)
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- Coral reef
- Limits of prominent lava flow within volcanic formation
- Prominent swamps
- Roads (vehicular)
- Roads (non vehicular)
- Tracks
- Flowing Streams
- Stream channels
- Village — Vaitolo
- Village (abandoned) — Mutia
- Spot height in feet above Sea Level — 200'
- Petrological samples (locality and number) — PT620
- Phosphate samples — P413

INDEX TO ADJOINING SHEET

MAP 1 SAVAI'I; MAP 2 'UPOLU; TUTUILA; AUNUU; Pago Pago Naval Station; OFU; OLOSIGA; TA'U; MANUA GROUP; ROSE; 172° W; 171° W; 170° W; 169° W; 14° S

SCALE

1 : 100,000

0 1 2 3 4 5 MILES

Compiled from data obtained from the Lands & Survey Department Apia Western Samoa. Additional Surveys and Geology by D. Kear, and B. L. Wood, New Zealand Geological Survey, and S. Poston, Public Works Department, Apia. Some geological boundaries from soil survey of A. C. S. Wright, New Zealand Soil Bureau, 1956

Published by the Department of Scientific and Industrial Research 1958

R. E. Owen, Government Printer, Wellington, New Zealand

GEOLOGICAL LEGEND

SEDIMENTARY ROCKS AND MARINE TUFF

HOLOCENE	Alluvium Swamp talus etc. (including some Tafagamanu sand)	A
	Tafagamanu Sand (coastal strip of coral sand about 5 ft. above sea level)	T
	Nu'utele Sand (coral sand 15 ft. above sea level)	N
MIDDLE AND LATE PLEISTOCENE	Lalomauga Alluvium (terrace gravels in Falefa Valley)	LA
	Talus from Fagaloa Volcanics	Ft
	Vini Tuff (palagonite tuff of eastern islands and Apolima Island)	V

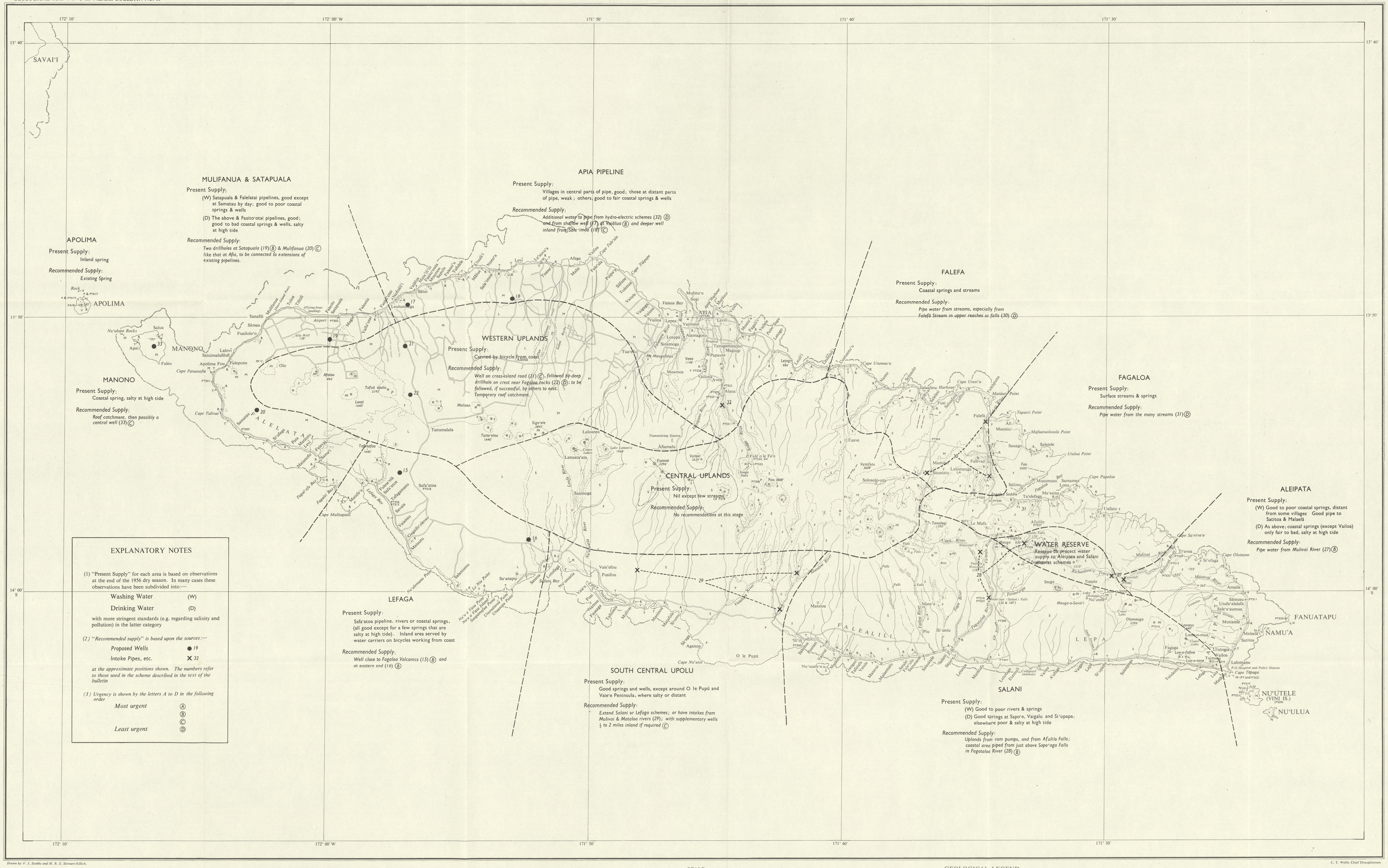
VOLCANIC FORMATIONS

			Cones
HOLOCENE	Aopo Volcanics (historical)	A	a
	Puapua Volcanics (reef-covering)	P	p
	Lefaga Volcanics (narrow reefs offshore)	L	l
MIDDLE AND LATE PLEISTOCENE	Mulifanua Volcanics (wide reefs offshore)	M	m
	Salani Volcanics (wide reefs, deep soils, canyons)	S	s
EARLY PLEISTOCENE OR PLIOCENE	Fagaloa Volcanics (steep eroded relief, deep soils, drowned coasts, narrow reefs)	F	f

● None on this sheet

NEW ZEALAND GEOLOGICAL SURVEY

HYDROLOGY OF UPOLU



Drawn by V. J. Stubbs and H. R. S. Stewart-Killick. — C. T. Webb, Chief Draughtsman.

GENERAL REFERENCE

Geological boundary; Faults (inferred only); Dip and Strike; Escarpments, cliffs; Centre of Eruption (commonly small crater); Inland Springs; Coral reefs; Limits of prominent lava flow within volcanic formation; Prominent swamps; Roads (vehicular); Roads (non vehicular); Tracks; Flowing Streams; Stream channels; Village — Lataitai; Village (abandoned) — Avele; Spot height in feet above Sea Level — 480'; Petrological samples (locality and number) — PT519; Phosphate samples — P616

INDEX TO ADJOINING SHEET

MAP 1 SAVAI'I; MAP 2 UPOLU; TUTUILA; AUNUU; Pago Pago Naval Station; OFU; OLOSEGA; TAU; MANUA GROUP; ROSE; 172° W; 171° W; 170° W; 169° W; 14° S

SCALE

1 : 100,000

0 1 2 3 4 5 MILES

R. W. Willett, Director

Compiled from data obtained from the Lands & Survey Department Apia Western Samoa. Additional Surveys and Geology by D. Kear, and B. L. Wood, New Zealand Geological Survey, and S. Poutoa, Public Works Department, Apia. Some geological boundaries from soil survey of A. C. S. Wright, New Zealand Soil Bureau, 1956.

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GEOLOGICAL LEGEND

SEDIMENTARY ROCKS AND MARINE TUFF

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	Tafagamanu Sand (coastal strip of coral sand about 5 ft. above sea level)	T
	Nu'utele Sand (coral sand 15 ft. above sea level)	N
MIDDLE AND LATE PLEISTOCENE	Lalomauga Alluvium (terrace gravels in Falefa Valley)	LA
	Talus from Fagaloa Volcanics	Ft
	Vini Tuff (palagonite tuff of eastern islands and Apolima Island)	V
EARLY PLEISTOCENE OR PLIOCENE		

VOLCANIC FORMATIONS

		Cones
Aopo Volcanics (historical)	A	a
Puapua Volcanics (reef-covering)	P	p
Lefaga Volcanics (narrow reefs offshore)	L	l
Mulifanua Volcanics (wide reefs offshore)	M	m
Salani Volcanics (wide reefs, deep soils, canyons)	S	s
Fagaloa Volcanics (steep-eroded relief, deep soils, drowned coasts, narrow reefs)	F	

* None on this sheet

NEW ZEALAND GEOLOGICAL SURVEY

BATHYMETRY OF APOLIMA STRAIT AND APIA COAST

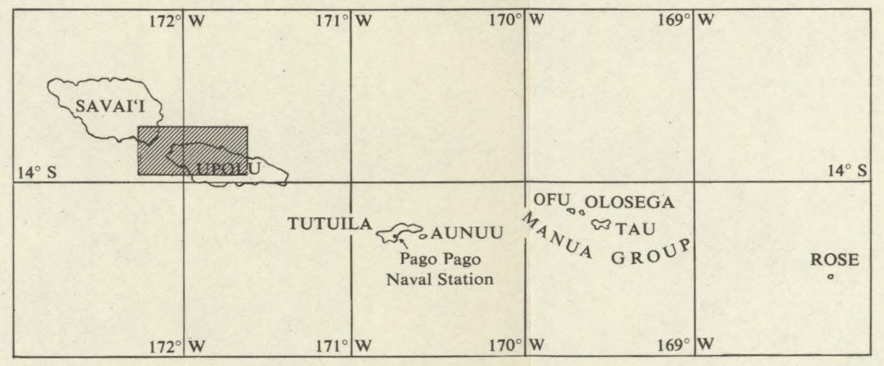
MAP NO. 3 N.Z.G.S. BULLETIN NO. 63

1:100,000

Drawn by H. R. S. Stewart-Killick

C. T. Webb, Chief Draughtsman

LOCALITY MAP



SCALE

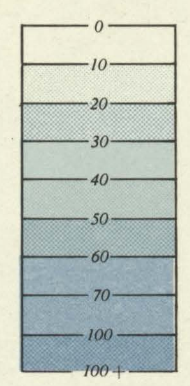
1 : 100,000

0 1 2 3 4 5 MILES

R. W. Willett
Director

LEGEND

FATHOMS



Bathymetric contours compiled by D. Kear and B. L. Wood, New Zealand Geological Survey
from data supplied by the Hydrographic Branch, Navy Department 1956
Published by the Department of Scientific and Industrial Research 1958

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