Geology and Offshore Mineral Resources of the Central Pacific Basin

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THE GEOLOGY OF THE SAMOAN ISLANDS

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ABSTRACT

The Samoan chain consists of high volcanic islands, atolls, and submerged reef banks near the southwest margin of the Pacific plate. The chain is unusual, particularly when compared with the Hawaiian chain, because the islands are volcanically active on both the eastern and western ends of the chain, the islands are larger westward, the easternmost edifice is an atoll not an active seamount, and the chain consists dominantly of alkali rather than tholeitic lavas. While geological studies of the Samoan group are limited, the existing results are consistent with a hot spot origin similar to Hawaii, complicated by continued reactivation of volcanism on Savaii. The continuing volcanism on Savaii is believed to be the result of deformation of the margin due to lithospheric dilation, as the plate bends where it approaches the Tonga Trench subduction zone. The dominance of alkali volcanism in this island chain has recently been associated with a geochemical heterogeneity in the underlying mantle.

INTRODUCTION

The Samoan Islands are a chain of high volcanic islands in the southwest Pacific Ocean. The chain consists of three high volcanic islands (Tutuila, American Samoa; Upolu and Savai'i, Western Samoa) and numerous atolls (Fig. 1). Reef banks and seamounts continue westward from the chain, constituting the Southwestern and Malaxean Trenches (Brocher, 1985). The first geologic studies of the islands were conducted by sailing vessels exploring the south Pacific. Several early geologic studies reported volcanic eruptions (1902-1914). Early geologic mapping took place in the 1940s and 1950s but little more was done until the 1980s. The islands of the chain, other than Rose Atoll, are young (less than a few million years in age). Previous workers have compared these islands with the Hawaiian islands because the geologic relations, ages, and orientation of the islands and submerged seamounts are similar (Fig. 2). The purpose of this chapter is to summarize the current state of our understanding of the origin and evolution of the Samoan island chain, and bring together the geologic information from diverse publications into a single summary.

Political Division of Samoa

The Samoan Islands have been divided politically since the mid-1800s. The islands of the Manua Group and the island of Tutuila are territories of the United States of America. Scenic Pago Pago harbor in Tutuila was used by

Figure 1. Map of the main islands in the Samoan island chain. Rose Atoll is a low coal atoll with two islets. The rest of the island chain consists of high volcanic islands. The islands of Samoa are larger to the west in the chain. The trend is the opposite of that observed in the Hawaiian chain.

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American ships as a coal fueling station; the harbor is now the home of the Pacific tuna fleet. In the 1800’s, Western Samoa was held under a tripartite protectorate comprised of Germany, England, and the U.S. In 1900, England withdrew from the agreement and the American and German interests divided the islands into American Samoa and Western Samoa. The League of Nations granted New Zealand a mandate for Western Samoa in 1914 and German holdings were expropriated. Western Samoa is now an independent nation but still maintains strong political and economic ties with New Zealand. American Samoa has remained politically linked to the U.S.

The Samoan island group has been politically divided for many years, and as a result the early geological studies and mapping of the islands were carried out by two groups with different approaches to defining geologic units. The geologic studies in Western Samoa were done by hydrologists and the basic mapping units were based upon geomorphologic relationships observed from aerial photographs with limited field mapping. In American Samoa, the early geologic studies were carried out by a volcanologist and the mapping units were based upon field relationships of volcanic units. Because the definitions and mapping techniques used are so different, the descriptions of the geologic units of these islands cannot readily be combined. Therefore, the geology of the islands of Western Samoa are described, followed by the description of the geology of American Samoa. Because the political divisions of the island group directly affects the geologic studies of the group, a brief summary of the historical background of the islands has been included in this text. If the reader is not interested in this background, the reader should proceed directly to the section entitled Geologic Exploration.

BACKGROUND

Volcanic Heritage

The word Samoa comes from the words sa la moa in the native Samoan language. The legendary name is derived from the volcanic origin of the land itself. According to Samoan legend, “the rocks cried to the earth, and the earth became pregnant. Salemo, the god of rocks, observed motion in the moa, or center of the earth. The child was born and named sa la Moa, from the place where it was seen moving. Salemo said he would become loose stones, and that everything which grew would be sa la Moa or sacred to Moa. Hence the rocks and earth were called sa la Moa or as it is abbreviated, SAMOA, according to Turner (1979).

Discovery and Early Exploration

Jacob Roggeveen is considered to be the modern discoverer of the Samoa islands in 1722. The islands were inhabited by natives at the time of the first encounter with Europeans. Roggeveen called them the "Saunuma Islands" after a captain in his squadron of ships. In 1768, L. Bougainville visited the islands, naming them the "Iles des Navigateurs" after observing the frequent use of canoes by the natives.

Captain James Cook heard of these islands while in Tonga in 1773 and recorded their names but did not visit. In 1789, a visit by La Perouse to Tutuala proved eventful. His second-in-command, Captain de Langle, died along with many crew members in a scene very similar to that in which Captain James Cook lost his life in the Hawaiian Islands. After the death of his crew members, La Perouse gave the island the name "Massacre Island"—now Tutuala. The bay on the north shore of Tutuala is still known as Massacre Bay (near Aasut). The historic event is of interest since the geologic features there played an important part in the events which transpired at the bay.

On December 12, Captain de Langle and 61 men in two longboats and two pinasses went to a village in a cove near their anchorage to collect water. Instead of a spacious and convenient cove, the men found a coral-filled cove with a
The Samoan islands were visited by Edwards in 1791, as part of the search by H.M.S. Pandora for participants in the mutiny on H.M.S. Bounty. A book by the captain and physician on this voyage (Edwards and Hamilton, 1913) describes many visits to South Pacific islands. Von Kotzebue visited the islands in 1824.

REGIONAL SETTING

The Samoan islands consist of a series of high volcanic islands, atolls and submerged reef banks, and seamounts which form a linear chain in the southwest Pacific Ocean. The chain trends in a southeast-northwest direction (Fig. 2), beginning near the international date line and extending westward, roughly 200 km north of the termination of the Tonga Trench, into a region known as the Northern Melanesian Borderland (Fig. 3, from Brocher, 1985). The Northern Melanesian Borderland is a complex region within the southwest Pacific where island arcs like the Tonga and Lau Islands, mid-plate features like Peggy Ridge, and seamounts of hot spot origin like the Samoan group, occur near the convergent margin of the Pacific plate and the Fiji Plateau.

Figure 3. Map of the Northern Melanesian Borderland (from Brocher, 1985) illustrating the major bathymetric features in the region. The Samoan and Fiji Islands are shown with a stippled pattern. The island contours and 1,000 and 2,000-m contours are shown.
The easternmost member of the island chain is Rose Atoll. Rose Atoll is a low carbonate bank. Other than the alignment of Rose with the remainder of the chain, no evidence exists to directly link the atoll to the Samoan group. Thus, previous workers have suggested it may be an old remnant of unrelated origin. West of Rose Atoll are the high volcanic islands that form an island chain similar in nature to the Hawaiian or Society island groups, with the exception of the island of Savaii. Savaii, on the western end of the chain, is still volcanically active. Further to the west are the submerged seamounts and reef banks described by Brocher (1985). Age dating of rock dredged from these banks suggests these banks are a continuation of the Samoan seamount group.

GEOLGIC EXPLORATION

Previous Studies

The first geological explorations of Samoa were reported by Dana (1849) as part of the U.S. Exploring Expedition under Lt. Charles Wilkes. Dana spent a very limited time on Samoan; his visit to the islands was restricted to the time required by the expedition to generate a hydrographic map of the island. Despite his short visit, the observations of Dana show an obvious insight into the geology of these islands. As a result of Dana's visit to these islands and others, he published numerous manuscripts, including "Geology of the Pacific Area" (1846) in the Wilkes expedition volumes, "Corals and Coral Islands" (1872) and "Characteristics of 'volcanoes'" (1899).

Dana noted the youthful appearance of the western district of Samoa (Savaii), which contrasts with the greater age of the central portion of the chain (Tutuila). He felt that these islands formed from two volcanic fissures, each of one age equivalent to Tahiti (in the Society Islands) and Kauai (in the Hawaiian islands), and a second contemporaneous with the present reefs. Chemical and petrographic studies of the lava flows have been reported by Moble (1902), Kaiser (1904), Klaatsch (1907), Jurasen (1908), Daly (1924), Bartrum (1927), Macdonald (1934, 1969), Sice (1968), Hubbard (1971), Hedge et al. (1972), Hawkins and Natland (1975), and Natland (1975, 1960).

Descriptions of volcanic eruptions include those of Angenheister (1909), Anderson (1910), Friedlander (1910), Grevell (1921), Vose Bulow (1966), Friedericci (1910), Reinecke (1905, 1906), Sapper (1905, 1906, 1911a,b, 1912, 1915), Schmittbusch (1911), Wegener (1902, 1903a,b), and Bryan (1941). Geologic studies of the islands include those by Friedlander (1920), Park (1914), Thomson (1921), Stearns (1944), Kear and Wood (1959), Sice and McCloy (1960), Hawkins and Natland (1975) and Natland (1975, 1980). Isotopic and geochemical studies have been conducted by White and Hoffman (1963), Newman et al. (1984), Rixon and Craig, 1982, Matsuda et al. (1984), Wright and White (1987) and Wright (1987). Dating studies include those of Richard (1982), Matsuda and others (1984), Natland and Turner (1982), Duncan (1982), and McDougall (1985). Geophysical studies include a paleomagnetic study by Taring (1962, 1965) and Keating (1985a), gravity studied by Mackenzie (1963) and Robertson (1987) and an earthquake report by Needham et al. (1982). A sedimentological and bathymetric survey of the Samoan archipelagic apron, discussing deformation of the apron in the Tonga Trench, was published by Longstaff (1975). Nearshore sedimentologic studies were reported by Daly (1924) and Dingleger et al. (1986). Offshore pelagic sediment distribution is summarized in the geologic map of the Circum-Pacific Region, Southwest Quadrant (Patterson, et al., 1988). Many of the early geological reports of Samoa are written in German and are not readily available. Fortunately, Thomson (1921) published a thorough review in English of most of these works. Thomson summarized the petrology as known in 1921 (Table 1).

| Table 1. Volcanic Rock Types on Samoa (From Thomson, 1921) |
|-------------|-------------|-------------|-------------|-------------|
| Savaii:     | Olivine basalt, olivine-enstatite basalt, olivine trachyte, nepheline basanite, phonolite. |
| Apolima:    | Nepheline basalt. |
| Upolu:      | Limbargrite, olivine basalt, olivine basalt- perphyrite, trachyandesite, nepheline basanite. |
| Tutuila:    | Limbargrite, olivine basalt, andesitic basalt, spilite, nepheline basanite, trachydolerite, nepheline basanite, trachyte, alkali trachyte, phonolitic trachyte. |
| Aunu:       | Trachydolerite. |
| Ofu:        | Olivine basalt. |
| Olosega:    | Olivine basalt. |
| Ta'u:       | Olivine basalt. |
GENERAL DESCRIPTION OF THE ISLANDS

Western Samoa

Kear and Wood (1959) reported on the geology and hydrology of Western Samoa. They recognize a general structure on Upolu of deeply eroded and dissected volcanic strata (assigned a Pliocene or early Pleistocene age), largely buried by late Pleistocene and Recent lavas. They assign the name Pagalu volcanics to the oldest of these rocks, largely on the basis of their weathered appearance, consisting of 2a and pahohoe flows along with associated dykes, tuffs and cone deposits. They point out that these rocks characteristically form steep-sided high, mountains with erosional slopes of 25-50\(^\circ\). Of considerable interest is their observation that the original dips on the exposed surfaces suggest that these volcanics were extruded from vents that are oriented approximately parallel to those of the younger lavas.

Rocks from each of the younger mapped units unconformably overlie and fill valleys eroded into Pagalu volcanics. Most of these units are olivine-rich basalts which strongly resemble one another petrologically. The features used to differentiate between the rock units include (Kear and Wood, 1959):

- Saini Volcanics: deep soil and weathering; evidence of pre-Mulianna canyon cutting.
- Mulianna Volcanics: the existence of wide barrier reefs existing offshore of these outcrops; only shallow stream channels.
- Leqafa Volcanics: lack of dikecrop; only narrow fringing reefs present offshore of these outcrops.
- PuaPua Volcanics: thin soils; lava flow offshore and flows on rocky (or "gravelly") coasts; ubiquitous as wide pahohoe structures form broad domes.
- Aopo Volcanics: cones erupted in last 200 years, fresh porphyritic pahohoe flows and aa flows common only around cones which fill older valleys and spill out over coasts to fill lagoons and cover the barrier reef.

Kear and Wood (1959) note that the volcanic cones are plentiful on Upolu and Savaii and that the degree of weathering, dikecrop, and decay of the cones varies, reflecting their Salani to Aopo ages. The largest cones occur between 600 and 900 m above sea level on Upolu, and up to 1800 m on Savaii. The cones vary widely in form, some having minor amounts of ejecta and giving rise to major lava floods, while others form simple single cones of cinders and scoria. The younger cones are generally black with veins of glassy cinder. As the rocks weather, they tend to turn reddish in color, and the fester-grained materials are altered to clay, forming a reddish clay soil littered with blocks of scoria.

Savaii

The island of Savaii is by far the largest island in the Samoan chain. Using the definitions and mapping unit of Kear and Wood (1959), the oldest rocks observed on the island are situated on either side of the Vaipouli River on the north shore of Savaii (Fig. 4). This unit displays considerable relief and deep weathering. Paleomagnetic studies of Savaii (Keating, 1985a) indicate that these rocks are characterized by normal polarity magnetization. Based upon the magnetic reversal time scale, we believe these rocks are likely to correspond to the Gauss Normal Chron and therefore are 2.5 million years old or older. Radiometric dating of these rocks has been undertaken by Ian McDougall. The results of these studies when published will much more accurately define the ages of these rocks.

![Figure 4. Site map for the island of Savaii showing the location of sites referred to in the text. Several site names have changed since their publication in geological texts early in the century. The new names are used in this map and where possible both the older and newer names have been included in text.](image-url)

As erosional unconformity separates this old unit from overlying rocks; however, all of the overlying rocks sampled on Savaii are also normally magnetized. The younger rocks (Salani, Mulianna, PuaPua, and Aopo formations) are believed to correspond to the Brunhes Normal Chron and be less than 300,000 years old (Keating, 1985a). No rocks of reversed polarity were found on this island in Keating's study. Tarling (1966) published a map of sampling sites.
The Salani volcanics are exposed in a wide swath extending north-south in central Savaii. These volcanics are moderately weathered, and a thick soil cover is present. Much of the Salani volcanic unit is drained by the Malito River, Latu River, Tapiaga or Lafa River, and Faleata River. The large area in eastern Savaii centered around Taputapu is mapped as Salani volcanics (Fig. 5). However, no large drainage systems like those elsewhere in Salani volcanics are present, which is suggestive that these volcanics are not the same age. Evidence from paleomagnetic studies of outcrops in this area confirm this observation (Keating, 1985a), and indicate that this may be a new (presently unknown) volcanic unit.

Outcrops of the Mulifanua formation are extensive on Savaii. Most of the western half of Savaii is characterized by this rock unit, as well as large coastal areas on the north shore near Fagamalo and on the east coast from PuaPua to Saleleoga. According to Kear and Wood (1959), "the Mulifanua may be distinguished from the Salani volcanics largely on their lesser erosion and weathering. The lack of deep water courses and the angularity of surface boulders are the most important criteria." In western Savaii, the Mulifanua volcanics "rest on a weathered basalt that is considered to be Salani."

The outcrops of Mulifanua and Salani units appear concentrated on the axis of a spoke-like rift system developed on the eastern end of the island (Fig. 6). The PuaPua and Aopo volcanics, however, appear to originate from a later rift that is longitudinal to the island.

The PuaPua volcanics are distributed almost radially around the island of Savaii (Figs. 5 and 7). The PuaPua flows are extensive. The evidence from the historic eruptions of the eastern coast indicates that these flows are the result of the 1926 eruption. The PuaPua flows extended to the east and south, and the PuaPua was the name given to the last eruption of the island. The lava flow from the PuaPua formed a large shield volcano that extended to the south of the island. The PuaPua flows are characterized by a low viscosity and are capable of flowing over long distances without losing their shape. The PuaPua flows are commonly found in the eastern part of the island, where they have buried the older volcanic rocks and the coastal areas.

where oriented hand samples were collected. Reversed polarity was found on the western coast within a unit mapped as Mulifanua. His summary table however indicates that all of the igneous formations on Savaii are normally magnetized. Tarling (1966) suggested all the rocks on Savaii are less than 1 m.y.

Figure 5. Geologic maps of the islands of Upolu and Savaii based upon the mapping of Kear and Wood (1929). The formation names are abbreviated in the figure (F = Fagafga, S = Salani, M = Mulifanua, L = Lefaga, P = PuaPua, A = Aopo). Also shown is the geologic map of Tutuila based upon mapping by Stearns (1944). The formation names are abbreviated in the figure (T = Taputapu, L = Leone, P = Pago, A = Alofa, and O = Oloomoana).

Figure 6. Map of Savaii showing the location of historic lava flows, cones, and the inferred rift zones. Based upon geologic map of Kear and Wood (1959). The dots represent cones and the dashed lines are inferred rift zones.
Figure 7. Maps of Samoa and Upolu showing the location of the young lava flows. The dotted lines indicate the location of coral reefs off shore, based upon mapping by Kears and Woods (1959) using aerial photographs. The formation names are abbreviated in the figure (F = Fagaloa, S = Salani, M = Malifanesa, L = Leifaga, P = PasaPasa, A = Aopo).
GEOLOGY OF SAMOA

tions indicates that these extensive lava fields can be generated in a matter of only a few years. The paleomagnetic evidence suggests that the PuaPua volcanic unit could be divided into two chronostratigraphic units. Flows from the Sina (Figs. 4 and 5), the Sili area (south coast), the Sasiia area (north coast), and Tafuiapu area (western tip of the island) are likely to be grouped into a new mapping unit (Kesting, 1985a).

The Arso volcanics (Fig. 7) are historic lava flows. The paleomagnetic studies of Kesting (1985a) show one flow near Arso, mapped as Arso volcanics, giving directions similar to the PuaPua volcanic unit (sensu stricto). Since the area, however, had been bulldozed and the flow material removed and used for road mantles, it seems likely that overlying Arso flow material was removed and the PuaPua unit sampled rather than Arso unit.

Asau Bay

Asau Bay is located on the northwestern coast of Savaii. The eastern margin of the bay (Uluoa Point) is bordered by PuaPua volcanics that are flat-lying paleohole lavas which filled the pre-existing lagoon and buried the reef. The remainder of the bay is formed by Mullifanus lavas. These lavas are highly vesicular nearly flat-lying basaltic lava flows. Near the water the lava flows are very fresh in appearance, lacking substantial weathering.

A well-developed coral reef exists offshore from Matavai (or Uluoa Point, depending on the map used) to Fagasa. There another PuaPua flow buries much of the lagoon (Fig. 2), while much of the area from Fagasa to Satus is mapped as Mullifanus volcanics. The lack of a barrier reef westward suggests it is a younger unit, perhaps PuaPua. A barrier reef is reestablished near Pupu.

Figure 8 illustrates a typical cross section of the reef structure buried by lava flows in the Asau Bay area. Figure 10 illustrates the structure likely at Matavai or Uluoa Point, where the most recent flows now bury the reef. If this area of Savaii has subsided substantially due to crustal loading, a complex structure similar to that in Figure 10 would develop. Menard (1960) reported similar areas of the island of Hawaii have subsided at a rate of 2 to 3 m/my. Local water well drillers have reported multiple attestations of the basic reef and lava sequence occurring at Asau Bay. The multiple repetitions of reef material and lava flows have been observed in Hawaii in cone samples from geothermal holes at depth 1635-1767 m on the southeast rift zone of Kilauea volcano.

Thomson (1931) pointed out that the geomorphology of Savaii is similar to that of Manu'a. The original observations by Thomson, however, result from arduous field work by Friedlander and R. Williams. Williams made a crossing of the island in 1907 from Matavai (north coast) to Tufu (south coast) (assumed to be Tufu stream on modern maps) crossing the ridge which forms the "backbone" of Savaii, east of its highest point. Friedlander traversed the ridge from west to east. Both Williams and Thomson used the altitude they gained along this ridge in order to view the cones and craters which mark the ridge. In the western part of the ridge (near the, in Samoa) where the vegetation is poor, well-preserved volcanic cones can be observed. The central part of the ridge is covered by dense forest and contains larger cones separated by old lava fields. To the east, numerous cones are present which are hard to be seen in the bush until reaching their base.

In one of these eastern cones, a small lake, Matauafono, is found. The crater rises 40 m above lake level. The altered ash of the cone makes the lake bottom impermeable. This cone would make an excellent site for paleomagnetic secular variation studies (using pol-

Figure 8. Aerial photograph of the southern coast of Savaii. In this photograph the lava flows cover the reef. Subsidence is occurring and new reef is growing on top of the lava flow. The cross section of the geologic structure would be similar to that shown in Figure 10.

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Figure 9. Cross section of a coral reef (top) showing the structure of a typical barrier reef on the margin of a Pacific Island, after that of Holmes (1945). An idealized cross section of a coral reef off Savaii or Upolu is shown in the bottom figure, where the lagoon has been filled by lava flows.

...for dating purposes, Mafane Cone south of Tavea also contains a swampy flat bottom (shown as a lake in road maps) which would be suitable for similar work. The cone is densely forested.

On the south coast near Tagg, between Nu'u and Tufu Stream are fresh-looking lava fields which appear to come from a neighboring small cone. These flows are likely to be slightly older than the written record, since some old Samoan songs are said to refer to these eruptions (Thomson, 1921).

On the peninsula of Taiua, there are small well-preserved cones. The outer slopes consist of well-stratified tuff. Thomson (1921) reports that at the bottom of these cones, a meter above sea level, is the entrance of a lava tunnel. These cones which dot the ...matiri (prominent axial ridge) mark the fissure zone which is the area of concentrated...

Figure 10. Cross section of the structure off Asau Bay, in northwest Savaii. There, several episodes of reef growth and subsequent burial by lava flows have occurred, making the geologic structures very complex. The sequence includes alternating layers of lava, coral, beach sands, and ageogene tuffs. This cross section was drawn on the basis of conversations with water well drillers who have drilled numerous wells on Savaii (personal communications, 1983).
Apolima

Apolima is a small islet about halfway between Savaii and Upolu. An excellent view of the islet is gained by skating the open ferty from Upolu to Savaii. A single crater wall opens to the north. The bottom of the crater is only a few meters above sea level. The two slopes of the crater wall slope at 30-40° while those of the outer wall are about 60°.

The tuff is a compact brown palagonitic tuff containing boulders of massive and porous lavas, fragments of coral, and massive mollusks (Thomson, 1921, derived from an account by Friedlander, 1910).

Thomson (1921, p. 33) notes that owing to the imperious nature of the tuff, the island has continuously running springs and a small stream draining to the north across the bottom of the crater. It is this fact which renders the island habitable. Weber describes the tuff as palagonite, the glass lapilli being penetrated by spongy filled with zeolites, cavities, and some sideromelane. There are inclusions of large olivines and microcrystals of augite, but no iron-ores, and lapilli of basaltic nature. A dense brownish stone, evidently one of the massive boulders mentioned by Friedlander, is described as a nepheline basalt, with large phenocrysts of rounded and somewhat serpentinitized olivine in a groundmass consisting of brown-serpentine augite, some biotite and iron ores, a few needles of apatite, and a little nepheline.

Masono

Masono lies between Apolima, and Upolu (Fig. 11), within the barrier reef which lies off the west end of Upolu. Tulaga, to the west, contains a lava tunnel opening at sea level, but no crater. The slopes to the southwest are dominantly coral sands with occasional outcrops of vesicular basalt. The rocks at the summit are more massive but highly weathered. The springs on the latter are brackish.

Upolu

Like Savaii, the island of Upolu has a prominent metamorphic or axial ridge, which appears to be the major axis of future eruptions. Cones are distributed abundantly along the central axis of the island. In the northwestern part of the island a series of well-formed eruption cones and neighboring lava flows that appear fresh. Afafou Hill, however, is composed of a finer-grained, light-colored, less vesicular rock.

The south shore has numerous steep promontories of volcanic rock. Along the eastern shore similar outcrops exist. On the southeast coast there are several bays with steep-walled valleys and beautiful high waterfalls coming from high valleys. Thomson reports that a dense basaltic dyke cuts through a corner, lighter rock of andesitic appearance (fracture?) at Samanu.

Thomson (1922) also provides an excellent description of lava tubas on Savaii. He states that "the formation of lava-tunnels in the Matavai eruption has already been mentioned. Such tunnels are a characteristic of basaltic eruptions in the Kilauea type, and have an almost circular cross-section while the flow is active, but when the supply of lava ceases that the tunnel drains out, leaving only a little in the bottom, so that a cooled tunnel has an almost circular section except for a flat bottom. In any tunnel, the height and breadth are remarkably constant, except when branching takes place. Stalactites composed of fused lava formed by the burning of the inflammable gases discharged from the lava flowing below may often be observed hanging from the roof, and young stalagmites also have stalactites on the walls, and coatings of soluble salts, chiefly sulphates."

Thomson (1921) suggested that the hollow shapes of lava tubes would lead themselves admirably to ore-depositions. If the rocks enclosing these contain the more valuable metals in sufficient quantity, or the area large, the same under the influence of meteorologic and solutions. In discussing this subject with Dr. Jaggard of Killean, he surmised that the lava tunnels were not very permanent structures and were probably filled with laves from later eruptions, giving rise to intrusive bodies of pipe-like form. In Savaii, however, this does not seem to have been the case, and in the extinct lava flows, both of Savaii and Upolu, lava-tunnels are fairly frequent occurrences. They have, however, been considerably modified by the falling of rock from the roof and sides, and have lost their original nearly circular and very regular cross-section.

Two large tunnels in Savaii are known to have been used for refuge, one at Pa'omanu on Upolu and one near Va'o en Savaii. The one on Upolu has not been inhabited in recent years; however, the floors of the cave are stacked with rocks that create sloping terraces similar to the terraces of contemporary typical Samoan homes, called fales. In addition, charcoal, marine shells, and ashes have been found.
In this cave, Thomson suggests that up to 100 individuals could have slept there.

Von Buelow (1936) describes the Savaii cave as "the cave of the non-fighting tribe." At the time of warbing between the people of Safune and the rest of the island, about the end of the eighteenth century, the tunnel was supposed to have been used as a refuge with food stored there.

At Safune, Thomson described a pool formed by the downfall of a blow-hole a short distance from the sea. There he describes a pool of water which is affected by the tide. The tunnel lies roughly a meter below the surface and opens at the seaward side, giving rise to a bathing pool. At low tide, the pool has fresh water. Similar pools are seen around Savaii and Upolu. It is interesting to note that similar pools are present on the Puna and Kona coasts of the island of Hawaii.

Another interesting cave is reported in old lava at Tapiakolele on the east side of Savaii. Here, in a tunnel which has fallen in over some distance, a stream bed has formed that, when followed, ends abruptly in the tunnel. The mouth of the stream is occupied by a deep pool. Evidently you must swim the deep pool to proceed further in the tunnel, and therefore Thomson did not explore it further. He noted, however, in another tunnel nearby, that the floor of the tunnel was covered with a combination of guano (from local birds) and the chitinous remains of insects.

Elsewhere, Kerr and Wood (1959) reported other tunnels free of guano and containing only insect remains. The bird population in Savaii is still quite a varied one, which stands in marked contrast to most Pacific islands. This may well reflect a much less dense population of animals and humans on Savaii.

Lava Slopes

The lava surface slopes on Upolu are generally moderate, between 1° and 15°, and slope seaward. These slopes flatten as they reach sea level, where the lava flows have spread out onto the lagoon and reefs. Daly (1934) observed that the lava slopes on Tutuala ranged from 0° to 20°, with an average of about 10°. He suggests that the lava flows were extruded from fissures nearly parallel to the axis of the island. Most flows dip away from these central fissures and sea cliffs cut their down-dip edges. Isolated central vents can be associated with two ruff cones at Steps Point, Atuina Island, the eastern offshore vent, offshore vents near Coconut Point, and off Tuilapai inlet on the western coast of Tutuala.

Streams and Erosional Features

Kear and Wood (1959) used stream erosion to measure the age of rocks in Western Samoa. They summarize with the following observations:

- Fagaloa Volcanics - youthful graded valleys
- Salani - amphitheater-headed canyons; deep, poorly graded valleys
- Multifanaua and Lefaga - dry water courses
- PuaPua - few, short, weakly eroded gullies, which give rise to small springs where the lava thinly covers older rocks (e.g., Siga Springs in southeast Savaii)
- The streams on Fagaloa rocks appear perennial. The stream patterns are dendritic. The initial radial drainage patterns appear to continue in younger rocks since the older volcanics and younger units seem to have similar drainage divides.
- Many valleys appear to be drowned, e.g., Fagaloa Bay, Faleata Valley and several valleys on the north coast of Upolu.
- The perennial streams on Salani rocks produce three landforms: widely spaced, deeply entrenched gullies with several falls (e.g., Fagaloa or Salani river); complex multiple gully systems; deep amphitheater-headed canyons.

Coral Reefs in Western Samoa

Stearns (1944) reported that living reefs around Upolu form fringing and barrier reefs. The fringing reefs range from narrow shelves to shelf flats 2 km wide. The fringing reefs consist of coral sands, shells, and detritus that in large part are bound together by algae growing on the surface. The fringing reefs tend to be exposed at low tide.

The barrier reefs are intermittent along stretches of the coast (Figure 7). In some places, they have been buried by lava, in other places rivers discharge into the sea and the turbidity is too high for corals to survive. In other locations, the flanks of the volcano have probably subsided as a result of fault slumps which drown the reef. A lagoon separates the barrier reef from the fringing reef. Stearns (1944) argues that "living barrier reef is not found along coasts composed of Plisocene rocks. Scarcely any fringing reef exists either... Barrier reefs are absent from the latest lavas also." Stearns suggests that Upolu was submerged so rapidly that reefs only grew to the surface where the Pleistocene lavas were gently slopeing. The rapid submergence was probably the combined result of a rapid sea level rise and island subsidence.

Stearns reports remnants of emerged reef at 1.5 m above the sea on the reef flat at Fagalii Bay. Wave-cut flats at 1.8-2.4 m above sea level are also reported. Matsushima and others (1984) collected sediments from shallow cores in Lefaga Bay in an attempt to date the sediments. The
samples analyzed were not autochronous coral. The age determinations suggest they were Holocene deposits. Sugimura and others (1988) reported on additional studies of sea level change based on outcrops and drilling in Western Samoa. Several wave cut notches in lava flows and occurrences of emerged beach rock were documented.

Kear and Wood (1959) have suggested that a correlation may exist between the age of the volcanic rocks and the distance offshore to the barrier reef. They suggest the following relationships:

1. Fagafusu: no living barrier reef or scarce fringing reef.
2. Salani and Muilifanua: wide reef.
3. Lefaga and younger: little or no reef.

Off the coasts of Salani and Muilifanua outcrops, the reefs tend to be barrier types where the lava slopes are gentle and fringing reefs form on steeper slopes. The extensive reefs around Savaii are in the process of being buried. In the area between Palauali and Faasaleleaga, the lava flow: have now built out beyond the old barrier reef.

Thompson (1921) concluded that many areas of the Upolu coastal plains had been depressed or downfaulted below the levels of coral growth causing the steep coasts and absence of bordering reefs. Thompson suggested downfaulting was the best explanation of the steep-walled harbors like Fagafusa Bay, particularly since valleys are absent around the bay, and no crag-like features are observed.

Sediments

The oldest sedimentary rocks in Western Samoa are the alluvium at Lalomanu on Upolu. Kear and Wood (1959) report that a tributary of the Palefa Stream was blocked by Muilifanua lava, and was subsequently filled with alluvium. The alluvium is preserved as terraces up to 9 m above stream level. Kear and Wood infer the alluvium is in part contemporaneous with the Pua Pua volcanics.

Sand Beaches

Few beaches in the Western Samoa islands have abundant sand. Thompson (1921) suggested that tsunami (tidal waves) may remove the sand. This suggestion is not consistent with observations of tsunamis which struck Hawaii in 1946 or 1960. Two factors obviously affect the formation of dunes: supply, and wind to transport the sand. On most islands there are sufficient breezes to move sand. Thus it is more likely a problem of there being too little sand. Sand off the coast of most islands is a product of erosion of reef material. In Samoa, the barrier reefs may provide a sufficient barrier to the sea that little wave energy reaches shoreward of the reef; thus little mechanical erosion of reef material occurs inshore and little sand is produced. Alternatively, sand may be produced continually and lost down the reef slope at the breaks in the reef. Beach sands are also limited within the Hawaiian Islands, where these processes are well documented.

Coral sands, soil and boulders form low cliffs, commonly in bays, about 1.5 m above sea level. Kear and Wood report a radiometric date of 2,300 years from a sample of this sand. Present day beaches of coral are partially cemented with calcite. The cemented beds, referred to as beach rock, dip seaward at about the same angle as the beaches.

Stearns (1944) reported that soundings off Upolu indi- cate a submarine shelf exists 46-55 m along the shore and 73-91 m, at a distance of 1.5-5 km offshore, which is similar in size and width to the drowned barrier reef on Tutuila. Stearns also correlates the submarine slope break to the shore line at the time of the "great erosional period" at least 122 m below the present shore line. Stearns concludes the drowned barrier reef rests on a thick section of marine and land deposits on an older platform.

Emerged Shorelines

Traces of a Recent +1.5 m stand of sea level are present in various places in the Western Samoa islands. These emerged shorelines form a strip of coral sand upon which most coastal villages occur and form spits (e.g., Molinu peninsula). In fact, the contact between these Tahagamau Sands and the Pua Pua volcanics is well exposed at the north end of the beach near Pua Pua village (see Kear and Wood, Fig. 20). This +1.5 m stand of sea level is commonly observed in the Pacific and is the result of a postglacial sea level rise accompanied by a warmer climate.

Traces of a +4.5 m stand of sea level are also found in Samoa. The associated deposits of Nuielele Sand occur at Gitaiva in southeast Savaii. At this site, the Pua Pua volcanics have a prominent beach cut into them at 4.5 m above sea level (Kear and Wood, Fig. 21). An overhanging cliff is found at the beach. At the foot of the low, irregular cliff is a small berm of fine, lightly cemented gravel, containing worn coral. Also exposed at the site is an ash bed within the basalt at about 4 m above sea level containing fragments of coral. This +4.5 m sea level is believed to be post-glacial because of its occurrence on reef covered Pua Pua volcanics; also, because of the correlation with similar beaches around the Pacific.

Kear and Wood (1959) stated that there is possible evidence of a +10 m sea level in the Vai Tufof, which could have corresponded with the last interglacial. They also report beaches near Fagafusa Bay southeast of Paleleia between 39 m and 60 m, which could be traces of a Ty- rhenian (last interglacial) or Milnean (penultimate interglacial).

On the east coast of Savaii a wide barrier reef 22 km long, as well as a fringing reef, is found. On the north shore, off Safune, a narrower reef occurs. Also, a narrow barrier

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reef occurs off Auala in northwest Savaii. The ends of these reefs are buried by younger volcanics. Thus, the remainders of the reefs are rock-bound. The extensive reefs around Samoan islands are in the process of being buried. In the area between Taluia and Fasaalealea, the lava flows have now cut beyond the old barrier reef.

Soils

Hamilton and Grange (1938) conducted the studies of the soils of Western Samoa. The studies along with those of Sclater and others (1938) show that the soils are relatively shallow, heterogeneous with frequent stones and boulders, and are rich from iron oxides derived from the basaltic lava.

During the 1950's, a soil survey was conducted on both Upolu and Savaii (Wright, 1963). A local classification system was subsequently devised based on the soil survey of Hawaii by Cline (1955); the system has been developed and reported by Morrison and others (1986). Schloth (1970) reports a number of soil analyses. A study of soils on the Lahanana research farm of the University of the South Pacific has been reported by Morrison and others (1986). Kear and Wood (1959) suggest that a good correlation exists between the depth of soil and the age of palaeoeho flows. On Savaii most of the historic flows have scarcely formed soil. The deepest soils occur on the Fagafoua volcanics in Western Samoa.

Alluvium

Aluvion from the mouths of streams was analyzed by Brantlett (1925). Most of the material is rock fragments, fine basal, trachytec, volcanic glass, and grains of magnelite, olivine, and feldspar. Brantlett reports that all of these are remarkably fresh and "show no evidence of weathering." A small percentage of calcareous or silicious organisms is also included; the material is poorly sorted.

Offshore Manganese Deposits

The land area of the Samoan islands is roughly 3,000 square kilometers while the offshore area within the Exclusive Economic Zone or EEZ (the area within 200 nautical miles of the islands) is about 150,000 square kilometers (Exos, 1982). In order to evaluate potential manganese (Mn) nodule deposits, sampling programs have been conducted in the basins surrounding the Samoan islands. Manganese nodules were found to be rare, and to be of low economic grades. Exos (1982) attributes the rarity to the high sedimentation rates caused by volcanic input of debris, which is detrimental to Mn nodule formation. Exos also concludes that the low grades of nickel and copper observed reflect the low production of plankton generally associated with deposits. Because the seafloor is well above the calcite compensation depth, calcareous plankton are not dissolved and do not release metals to the seafloor where Mag concentrations take place. Manheim and Lane-Bostwick (1989) point out the importance of the chemical character of the water mass. They have found that cobalt distribution within Ma crusts reflect regional highs and lows in the distribution of hydrothermal fluid discharge in the ocean. Commonly, at moderate depths (1–2 km), Ma crusts form on the upper slopes of sea mountains. In general, on relatively young seamounts (a few m.y.) these crust formations are very thin and do not constitute economic resources. Studies in the Hawaiian chain (McMartin et al., 1986) show thin Ma crusts of little economic value compared to the thick Ma crusts present on Mesozoic seamounts within the Central Pacific.

Two seamounts of possible Mesozoic age are present within the EEZ of Samoa, Machias Seamount and Rose Atoll. Machias Seamount is situated southwest of the Samoan Islands on the fracture arc of the Pacific plate near the Tonga trench. Early work on the seamount included dredges of the shallow summit (Hawkins and Natland, 1975). Cables, gravel, palaeoeho fragments, and coral were found in the dredges, indicating the crest of the seamount was formerly in sea level. A K-Ar age on a phosphate yielded an age of 940,000 ± 20,000.

Machias Seamount was surveyed using side-scan sonar as part of a Ma crust resource assessment. The images produced by the sonar showed that the seamount has been dissected by faults (Couliboure and others, 1989). The faults (Fig. 12) are parallel to the Tonga Trench and the flank of the seamount has dropped downward into the trench. The abundant faults yield a very complex bathymetry that would make mining on this seamount extremely difficult if a resource were present. Combining the evidence for a young age for the seamount (Hawkins and Natland, 1975) with the complexity of the bathymetry, the prospects for economic deposits of Ma crusts on Machias Seamount do not appear large at the present time. The age of Rose Atoll is uncertain. Without additional information, a resource assessment of the Ma crust is not possible.

Historic Volcanism in Western Samoa

The island of Savaii has experienced wide-spread volcanic activity in historic time. The flows associated with historic and geologically recent volcanism are shown in Figure 7. Thomson (1921) reviewed the volcanism and much of his description of the activity is included here.

Mauga Afi (about 1760)

Thomson (1921) writes,
Figure 12. Bathymetric map and sketch map of Nausia'as Seamount showing faulted structure of the seamount. The faulting is believed to be a consequence of deformation of the Pacific plate at the tip of the Tonga Trench subduction zone. (Figure from Coulbourn et al., 1989).
According to von Bulow and Tempest Anderson, the Samoans preserve a tradition of eruptions "about one hundred and fifty years ago" (A.D. 1790) that gave rise to a rugged and very extensive lava field, called O le Mu, between the villages of Asau and Aapo, on the north side of Savaii. This field is said to be more extensive than that recently created by the Matavanu eruptions, but is shown on the German Admiralty Chart with a length of eight miles and a half, and a breadth of only one mile and a half. It is still comparatively unaltered, preserving the 'wrinkled, knobbed,ropy, and sapoetry-like folds, and the general characteristics of the 'pahoehoe' type of lavaflow (Jenest), and is free of bush, which is rather surprising in view of the growth that has taken place already on the Matavanu lava. Jenest believes the flows came from Manua Af, a crater 5,249 ft (1,600 m) high, on the western slopes of the main ridge of the island, and attributes to the same source as a flow on the southern side of the ridge.

Aapo was surrounded and partially destroyed by these eruptions, and other villages were totally destroyed. The present village of Aapo occupies what is known in Hawaii as a hikupa, an area which a lava stream has flowed around and left as an island.

Friedlander describes the cone of Manua Af as a fairly steep scarp cone, 100 m high, with an elliptical crater, elongated east and west, 70 m deep. The western margin of the crater is broken, and here the lava flowed out in a westerly direction, turning to the north after a short distance.

Manga Mu of Aapo (1902)

Thomson (1921) states,

On October 30, 1902, eruptions commenced at a spot about three km northeast of Manga Mu and six and a half km southwest of the village of Asau. They were preceded, and accompanied by violent earthquake shocks, and for three weeks great detonations took place and flames were reported by Peet Mennel. The volcanic activity ceased after a few months. No previous crater was known at this spot, but according to Friedlander (1919) two hills were formed with an east-west extension, the larger with three well-formed lobate craters, and the smaller in the shape of a horseshoe. From both cones, lava streams issued and flowed 1 to 3 km in the direction of Aapo. Lava also welled out from a fissure on the side of an old crater to the south, and partially filled it. Wester (1903) states that a first crater, formed on October 30, furnished only lavas, but a second, about one km to the west, was formed on November 1 and was explosive for a shorter period.

Jenest describes the material of the 1902 eruption as a'a, consisting of fragments of all sizes, from cinders the size of peas to blocks many meters in diameter piled in wild configuration, and states that the lava is vesicular and scoriaceous. Friedlander (1910) describes the latter as black and metallic in luster, and very light and porous. Weber, who studied Friedlander's material, describes the lavas as a light porous slaggy form, referred to as feldspatic basalt consisting of phenocrysts of olivine, augite, and plagiodaste in a brown glass matrix with magnetite. Manga Mu is shown on the German Admiralty Chart as 'Ta'atat 1902 referring to its position as parasitic on Manua Af.'

Matavanu (1905-1911)

Thomson (1921) states that,

Just as Manga Mu is parasitic on Manua Af, so Matavanu may be described as parasitic on Fatu, an old crater occupied by a lake and lying a few km to the north of the main mountain tops of Savaii and a little over 2,000 ft (600 m) high. Before the eruptions, the place which is now the crater of Matavanu was a sort of elevated plain surrounded by mountains, about 11 km south of Matau. The eruptions began on August 4, 1905, and at first were of explosive nature, but severe earthquakes were experienced. From September 2 to 4, molten lava poured out and the flow advanced 3 km. The lava flowed at first to the northwest, filling up the upper ends of some valleys draining to Matau Harbor. Later it flowed both to the west and the northeast. In the latter direction following a tortured valley draining to the sea several km east of Matau and the lava itself reached the sea in December, 1905, at Faaopapa, filling up the lagoon between the coral reef and the coast and turning westward along the reef. Early in 1906 there was a great increase of activity, the lava destroyed the villages of Salago and Saleasua to the west, and it also flowed east and overwhelmed the villages of Taupatua and Maloua. The distance from the crater, following the winding and turnings, was about 13 miles (21 km), and the seafront covered was nearly 9 miles [15 km].

The villages destroyed by volcanism were not rebuilt; their names do not occur on modern maps of Savaii and they are not shown on the reality map (Fig. 4).

According to Anderson (cited by Thomson, 1921), the large, fresh lava streams sosa got crusted over on the surface with solidified lava, and the liquid

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lava continued to flow underneath. Even at the crater it seldom flowed over the lip, but generally entered holes and tunnels in the sides and flowed under- ground. The lava flow thus became honeycombed with channels of liquid or pasty lava, which occasion- ially came to the surface and flooded it with fresh sheets of lava; at other times the surface fre- quently floated up and was raised by the intrusion of fresh lava underneath, so that what had previously been the course of the valley now became the highest part of the field. Mr. Williams thinks that the lava must be in places 400 ft (120 m) thick.²

Thomson (1921) states, "where the coast was bordered by a coral reef, the lava quickly filled in the lagoon and thus extended the coast line. For a stretch where it was previously "iron- bound" i.e., formed of old lava not protected by a coral reef, as at Asuili, the lava flowed directly into deep water, and did not materially alter the outline of the coast. The flow into the sea continued, with only a day's intermission, from 1905 until 1910 or 1911. An immense amount of lava disappeared in this manner, estimated by Friedlander as many cubic kilometers, and four times the volume of that forming the visible lava fields (Sapper, 1913).³

"When the discharges into the sea were most active, Anderson related to Thomson (1921) that explo- sions were almost continuous, and the whole was obscured by clouds of steam from which fragments of red-hot lava and showers of black sand were seen to fall. This black sand formed beds capping the lava. Angenheister, in 1909, remarks that the explosions took pace every five to ten minutes. When the lava was flowing in lesser quantity, Anderson notes that explosions were much less noticeable, and the lava extended itself into bays and coves, and cooled in the form of a pillow lava.⁴

"The crater of Matavaru has been described in various stages by Jensen (1907), Angenheister (1909), Anderson (1910, 1911, 1912), Friedlander (1910), and Grevel (1911). The crater is a "broad slag-covered cone, with a steep-walled crater about 250 ft (75 m) deep, narrowly elliptical in form, and elongated about a quarter of a mile (0.4 km) from south southeast to north northwest. The northern end of the crater is partially fallen in, and the depression is extended in this direction by two fallen-in tunnels for another 100 yards (90 m) or so. Farther to the northeast, there is another disconnected downbreak, with a tunnel show- ing at the bottom in the northern end," according to Thomson (1921). Angenheister, noted in 1909, that the lava passed out through two tunnels to the north and one to the south, though there was no flow to the surface in the latter direction.

"The eastern side of the crater is composed of red ash below, grey ash above, capped by a 5 ft (1.5 m) layer of lava, which is covered on the outer surface by spatter slag. The western side shows lava flows with red ash between and above them, and the same 5 ft (1.5 m) layer of lava on the top. At the northern end, lavas come in wedge-shaped fashion, being unconfor- mably on the ash beds. Sulphur fumaroles are still active, both near the bottom at the north end and round the top of the talus slopes at the south end." The sulphur crystals are of the unstable monoclinic variety. In the 1900's, sulfur from the cone was being gathered by natives for medical purposes.

"The lava field from the base of the crater to the sea has an average slope estimated by Anderson at about 6°. The lava is mostly of the typical pahoehoe type, smooth over a wide area, though very irregular in detail, with typical small cracked domes and cor- rugated andropy surfaces. Near the crater areas of rough, broken lava simulating a'a are not uncommon, but they are made of broken pahoehoe, and I saw no typical a'a. Anderson's explanations of the origin of the a'a type of lava are diametrically opposed to those of Jagger, and the reason lies probably in the fact that he mistook areas of broken pahoehoe for a'a. For a more detailed description of the lava surface, the descriptions of Jensen (1907) and Anderson (1910, 1911, 1912) should be consulted. Furthermore, Thomson (1921) reports, "it is worthy of note that the growth of vegetation on the lavas of 1905 and 1906 greatly exceeded that on the 1894 or even the 1860 flows of Kilauea thus on the Matavaru flow presumably because of the moister climate." The lavas of Matavaru have been examined micro- scopically by Jensen (1908) and Weber (1909), but no analyses have been made. They are olivine-rich feldspar basalts with titaniferous augite, and generally with a consid- erable proportion of glass. The chilled surfaces of the pahoehoe flows are typical tachylites. Jensen states that the Matavaru lavas are richer in iron ores than any of the earlier flows," according to Thomson (1912).

**GEOLGIC MAPPING UNITS OF WESTERN SAMOA**

Kear and Wood (1959) produced the original geologic maps of Western Samoa. Their division of geologic map- ping units was based upon geomorphology. They identified
six geologic units and assigned them ages based upon rela-
tive weathering of Holocene to Pleistocene.

Fagafan Volcanics

The stratigraphically lowest, thus oldest, unit mapped
is the Fagafan volcanics. This unit is deeply weathered. The
wagged units include "two somewhat different landforms." Kears and Wood (1959: p. 30) report that, "one landform, possibly the older, has no part of the original cone form
remaining and forms steep high mountains with slopes up to
60°, rising as ridges above the gentle slopes of the later
lava flows. It includes dykes, which form bold vertical cliffs and
steep narrow ridges, often several hundred feet high. The
other landform, though steep locally, includes ridges that
deeply eroded seawards and could be the surviving parts of
the original cone surfaces. Some of the gently sloping
ridges have narrow flat tops on which the soil is strongly
leached, acidic, and now supports little more than wiry
grass. The steep offshore slope has prevented the formation
of coral reefs over much of the Fagafan coastline, and where
a reef is present, it is fringing."

Salani Volcanics

The Fagafan volcanics are overlain by Salani volcanics. Valleys and gorges cut deep into this volcanic unit. This
morphological characteristic was used to map the unit
serially. Often the Salani valleys are filled by younger lava
flows.

Salani volcanics consist of low angle lava flows that most
frequently can be traced to the cone or crater from which
they originated. The cones themselves are usually
weathered to the point that they are breached or contain
sufficient decomposed material to seal the bottom of the
cone and form crater lakes or swamps. The surfaces of
flows are often deeply weathered, and soil is often more than
30 cm thick. On the distal flows, over 30 cm of soil has
formed. Relict boles are often observed to show onion
skin weathering. The gorges formed by the river on Savaii
and Upolu cut deeply into Salani rocks. Often these gorges
are filled by younger lava flows. Valleys are common in
rocks of the Salani formation and are a distinctive mapping
feature. In many places, these valleys contain permanent
rivers. Elsewhere, the valleys can be dry much of the year.

Typically, a barrier reef exists offshore of Salani out-
flows. However, along the eastern part of the south coast of
Upolu, cliffs are found at the coast and the reef is close to
shore. Near Vaeva on Upolu, blowholes and sinkholes are
present, probably resulting from the collapse of blowholes.

The Salani rocks are fine grained gray to black por-
phyritic basalt which grade upward to vesicular basalt with
a rubbly 'a'a surface. The thickness of flows generally
average 1-2 m. The more weathered outcrops and presence
of large green olivine phenocrysts were used in the field
mapping to distinguish these rocks from the lithologically
similar but younger Mulifanua rocks (Kear and Wood,
1959).

Rocks of the Salani volcanics include picrite basalts,
olivine dolerite, and basalts showing late-stage deuteric
alteration and recrystallization. Olivine basalts constitute more
than 50% of the Salani volcanics sampled (Brothers, in Kear

The Salani volcanics are differentiated from the
Fagafan volcanics by their less weathered appearance, less
narrow landform (partial cones and craters), the absence
of dykes, less common occurrence of large olivine nodules and
phenocrysts, absence of andesites and trachytes, and the
presence of a well developed reef offshore. These basalt fill
valleys formed in Fagafan rocks, and top Fagafan ridges and
terrain. A well-developed soil horizon separates the
Fagafan and Salani volcanics at the Alofa power station on
Upolu. This deep soil horizon and the deep gorges cut
within the Fagafan are thought to reflect a substantial
erosional interval. Barrier reefs are generally present off-
shore of Salani volcanics.

Mulifanua Volcanics

Areas mapped as the Mulifanua unit are characterized
by dry shallow valleys and gullies, where flowing water is
rare. The weathering in this unit is "moderate." The flows
descend from "well-formed" cones, and are "almost un-
eroded." Boulders on the surface of the flows are angular
and onion skin weathering has not developed. In distal
portions of the flows, weathering can reach 30 cm. These
flows sometimes occur in valleys cut into pre-existing rocks.

Lefaga Volcanics

The Lefaga volcanics are the next stratigraphically
higher unit. According to Kear and Wood (1959), "The surface
expression is similar to that of Mulifanua rocks, except
that a's at the ground surface is more common, the
lava's appear to have flowed out into the lagoon area, and the
reef is relatively close inshore. Onion skin weathering
occurs locally, due possibly to the high fieldspar content."

Puamua Volcanics

The Puamua volcanics consist of young basaltic flows and
perfectly preserved craters. The cones have very little
weathering and the soil is thin. The rocky pahoehoe flows
cover pre-existing flows, fill gorges, and flow over pre-exist-
ing erosion scarps. The flows have low dips and form
relatively even surfaces. Extensive swamps have developed

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in low depressions. Locally, where slopes are steep, the flows consist of a 5 flows. Reefs are not developed offshore of PuaPua basaltis. Instead, the basalt is lapacal areas and cover pre-existing reef.

Aepo Volcanics

The final unit defined and mapped by Kear and Woods is the Aepo volcanics. These are "ropy, vesicular, porphyritic (feldspar and olivine) basaltis, with but little a's. Where the a's flows occur, it is blocky, loose and appears to have been transported on the surface of the flows and to have accumulated along the margin." These are the historical lavas.

Hydrology: Western Samoa

Kear and Wood (1959) attempted to establish a framework for understanding the ground-water gradients in Western Samoa. They attempted to map similar volcanic units, on the basis of the degree of erosion, in order to use the known depth of the water table (established by drilling) in a limited number of sites, and extrapolate away to areas where the water table was unknown. They suggested very low ground-water gradients "should be suspected in the younger volcanics that cover the majority of the territory." They suggested that wells be drilled to sea level to obtain water, because "apart from aera of the oldest rocks (Fagiaoa 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".

The Fagiaoa volcanics are the oldest rocks exposed in Western Samoa and are severely weathered. Kear and Wood (1959) state that the ground water "would generally be shallower, and available in smaller quantities than from younger less weathered formations..." Where Fagiaoa volcanics have been burned by younger lava flows, the water trapped above these older volcanics would provide a shallow water source.

The Salani volcanics are typified by large rivers which carry water to the sea. Significant losses of water occur along stream courses due to seepage. Inland springs occur where these rocks are covered by thin lavas of younger rocks.

The Mulifanea rocks absorb water readily and rarely is surface water present. Kear and Wood (1959) note that the scoriaceous nature of parts of the flows provides abundant water. Wells however must be drilled to sea level to obtain water.

Water obtained from the LeFaga, PuaPua and Aepo volcanics is characterized by high iron content. In general, the areas covered by these rocks have the poorest water supplies in Samoa except where the units are only a thin cover which overlies older rocks. On the island of Apolima, a surface stream emits water from the Vui Tuff. The stream never dries. On other islands, where the Vui Tuff is present, a non-trickling water supply is uncertain (Kear and Wood, 1959).

Geological History of Western Samoa

Kear and Wood (1959) outlined a possible geologic history for the islands of Western Samoa. They postulate two massive volcanoes built on a fissure or fissures trending 11°. The two volcanic piles merged undersea but emerged above sea level as two islands, Savaii and Upolu. The volcanoes would have first appeared as broad shield volcanoes, similar to Mauna Loa, Hawaii. The shoreline set that time has now subsided to 430 fathoms (853 m). Kear and Wood, (1959) referred to the early volcanoes as Fagiaoa volcanics. When volcanism ceased the volcanoes may have reached 1.8 km above sea level, during the late Pliocene or early middle Pleistocene.

During the early to middle Pleistocene these volcanoes were heavily eroded (Fig. 13), taking on an appearance similar to Oahu in the Hawaiian Islands, with steep rugged terrain and sharp peaks. Debris from the islands and reef growth produced offshore platforms, which have subsided and are 182 m below present sea level.

Kear and Wood suggest that renewed volcanism coincided with the postulinated glaciation (Fig. 14). The Vui Tuff is believed to coincide with the last interglacial period. Littoral cones and tuff cones were built along the coasts and Salani lavas flowed down valley walls, across reefs, and out onto the submarine slopes. Kear and Wood (1959) suggest the Salani volcanics reached 1 km above sea level in Upolu and over 1.2 km in Savaii. The Salani lavas covered most of the pre-existing landscape with the exception of eastern Upolu. Kear and Wood suggest the Salani volcanism in

![Figure 13. Profile of the island of Tutuila (American Samoa) illustrating the marine erosional surface, Former reef, drowned reef platform and barrier reef, as shown in illustration by Mayor (1920). Using the submarine profile of the islands of Western Samoa, Kear and Wood (1959) estimate the volcanoes rose 1.8 km above sea level in the late Pliocene to middle Pleistocene.](image-url)
creased the width of the islands to roughly the present outline. New coral reefs grew along the coastlines and have since subsided 16 m.

Erosion of Salani volcanic left gullies in the landscape. Where concentration of ground waters in Fagaloa volcanics reached the ground surface and were perched, streams eroded more rapidly into the Salani volcanics. Warm climate and increased rainfall in the last interglacial allowed amphibolite development in canyons of both Upolu and Savaii.

During the last glacial, extensive Muiliana lavas were erupted. The Muiliana lavas covered much of western Upolu. On the Savaii uplands, nearly 150 m of lavas accumulated. They also built a submarine fan on the southwest slope of Savaii. Littoral and submarine coasts in Apolima Strait occurred where lava entered the sea. Kear and Wood suggest a large part of the northern part of Savaii collapsed, as well as parts of the southeast and southwest flanks.

During the post glacial rise in sea level, barrier reefs grew (Fig. 15). Limited volcanism occurred, referred to as Lefaga volcanics. When sea level reached the present level, volcanism again occurred in southeast Savaii and buried parts of the wide barrier reef. A few small flows also filled valleys in Upolu.

In historic time, volcanic activity occurred in Savaii, which constitute some of the largest historic lavas flows in the world. These lavas buried older cones and cascaded into the sea.

**GEOLOGIC EXPLORATION OF AMERICAN SAMOA**

**General description of American Samoa Islands**

**Tutuila**

Tutuila is a long, narrow island with narrow irregular ridges forming the backbone of the island. Along its southwestern shore, a low unweathered volcanic peninsula has been added by relatively recent volcanic activity. The volcanic peaks of the older portion of the island are deeply eroded. In many parts of the island, loosely packed streambeds erode the volcanic slopes, creating steep slopes with thick accumulations of lateritized soils, separated by inter-valley ridges. Near the coast, the valleys widen and small coastal flats are developed. Drowned valleys form several embayments such as Faga Pago, Fagatou, Alofa, Vata, Fagau, and Nuu Sertosga Bays (Fig. 16).

Volcanic craters are absent over much of the island, since substantial weathering of the main island has left the island in a 'very mature' geomorphic stage. Volcanic invasions such as Mt. Foa, however, are clearly exposed by
Figure 15. Outline of the island of Upolu through time, as proposed by Stearns (1944). Stage 1 illustrates the proposed outlines of the island after extensive erosion of the island-building lavas. Stage 2 illustrates the outline of the island after the barrier reefs were drowned and volcanism was renewed. Stage 3 illustrates the present configuration of the island and the partial development of fringing and barrier reefs around the margin of the island.

the weathering, and thus form dominant landforms. The Lene Peninsula is a relatively low plain on the southwest margin of Tutuila that is generally unsettled by streams. There are prominent craters, Oloa Crater, Fogamaa Crater, and Fagatolo Crater. Oloa Crater, the summit of Aololoua, is slightly eroded. Nearly 200 streams are present on Tutuila (Davis, 1963). Many of the smaller streams are "ephemeral," i.e., they carry water only after precipitation and are dry during most of the year. The flows per person in streams come from springs and seeps which discharge ground water. Many only supply a trickle of water during dry season. The largest streams have a daily flow of a few million gallons (tens of thousands of cubic meters) of water per day in wet weather which is decreased to a few hundred thousand gallons (a few hundred cubic meters) per day in dry weather. Annual rainfall is approximated at 61 m/yr (Davis, 1963).

Aumua
Aumua is a small island situated off the southeastern coast of Tutuila. The island was formed by sub-marine volcanic activity. A tuft cone forms the eastern half of the island. It is breached on the eastern margin, forming Maumaa Cove. The weathering of Aumua tufts has produced an impermeable layer in the bottom of Aumua Cone where a lake and marsh have formed. The Tafusabutu marsh occupies a portion of the coastal flat west of the cone. Steward and west of this marsh, the coastal flat is covered by an appreciable volume of calcaceous sand and gravel (Davis, 1963).

Ofo and Olosea
Ofo and Olosea islands (Fig. 17) are remnants of a large volcano eroded to such a state that only two small steep islands remain, separated by a 200-m wide sea channel (Stearns, 1944; Sevick and McCoy, 1968).
entrance to the lagoon, the live reef grows in "long nearly parallel flat-topped, overarchling ridges all parallel with the line of the wave fronts of the breakers as they surge over the reef."

Lithothamnium is the dominant coral. Porolithon is the dominant algae.

Mayor (1924) reports two small islets on the atoll rim, Sand Islet and Rose Islet. A map made in 1839 shows Rose Islet the width of the atoll rim and forested. At the time of Mayor's visit in 1920 the islet covered only the inner half of the reef rim and only the southern half of the islet was covered by trees. In 1839 the island was described as rising 10 m above sea level. In 1920, the islet stood only 3 m above high tide with the tallest trees (Porolithon) 24 m high. The ground under the trees was covered by chocolate-colored humus which permeated the underlying lime coquina 2-3 m. Limited sand beaches were present around the atoll, 0.3-1.5 m in width at low tide. Cliffs of coquina 1.2 m high front the sea. Islets of these low cliffs was a rocky ledge 3-4 m above sea level. The grove of trees was confined to the region of coquina rock and did not extend over areas of loose calcareous breccia.

Sand Island is an accumulation of fragments of lithothamnium, shells and coral, which reach a height of 1.5 m above sea level in 1920. Mayor suggests the islet is submerged at times of storm induced high seas.

The upper surface of the atoll rim is a hard, flat surface with little sand. Mayor (1924) states: "...in most places it is awash at low tide, although in others it projects as a hard, smooth ledge about a foot (0.3 m) above low tide of the neap tides."

The atoll rim is cluttered with hundreds of large limestone blocks, generally 2 m high. Most of these blocks are probably storm-driven fragments of the reef, ripped off the outer rim of the barrier reef at times of severe storms or hurricanes. Mushroom-shaped pedestals still remain attached to the floor of the atoll rim..." Mayor argues, "the appearance of these boulders supports the view that the atoll rim was once about 2-2.5 m higher, in respect to sea level, than at present, and has been cut down to present sea level in recent times."

Mayor (1924) reports that after a diligent search he was unable to find any volcanic rocks on the atoll. Balances (personal communications, 1984) also reports that the only volcanic rocks he has observed on the island were cooking stones, brought to the atoll by Samoans when fishing and hunting turtles on the atoll. Courbyou (1842) however reported a number of volcanic boulders scattered on the sandy bottom of the lagoon. One weighing about 20 lbs was found in about 1 m of water, and appeared similar to those of the Samoan and Fijian islands. Wilkes (1852) reported boulders of vesicular lava were seen on the coral reef and were 20 to 200 pounds in weight, found among blocks of coral conglomerate. Mayor (1924) suggests Courbyou...
Figure 17. Geologic maps of the Manua Group, based upon maps by Stice and McCoy (1968) and later republished by Wegert (1981). The islands of Ofu and Olosega are shown at top. The island of Tau is shown at the bottom of the figure. In the upper figure the map symbols (in ascending stratigraphic order) are: A = Asaga Formation (the oldest map unit of Pliocene age), Tsl = pended flows of the Tusafania Formation, Tts = Tusafania Formation flows, T1ae = flows of the Tusafania Formation, N = tuffs of the Nua Formation. The remaining units, which are not separately designated are Quaternary sediments. The geologic map of Tau is shown in the lower figure. The map symbols used represent the following map units (in ascending order): Tls = lava flows of the Late Formation, Qhi = intra-caldera member of Late Formation, Qle = post-caldera volcanics of the Late Formation, Qte = ash, tuff, and olivine basalt of the Tusafania Formation, Qtp = pended lavas of Late Formation, Qlg = flows of Lastic Formation, Qlf = fossilized Tuff Formation, Qsi = alluvium. Qb = modern beach sediments. The remaining units which are not separately designated are Quaternary sediments.
The reports of basaltic basaltic are very important. It is assumed that Rose Atoll is an isolated old seamount, unrelated to Saxon volcanism. If it is an old seamount, a very thick carbonate cap would be expected. Johnston Atoll for comparison, appears to be capped by 1800 as of sediments (Keating, 1956). No basaltic fragments would be expected on the shallow slopes of an ancient atoll, and the observed basaltic fragments are likely to be transported lava rock fragments from the high Saxon islands by fishermen as suggested by Halusz (personal communications, 1984). By contrast, the numerous reports of blocks of lava on the atoll are suggestive that lava outcrops are present on the upper slopes of Rose Atoll, which would be consistent with a young age for the seamount that could be linked to volcanism of the Saxon chain.

Lipman and Taylor (1924) analyzed the soil within the pionia grove on Rose Atoll. From the descriptions of Mayor (1954) and Lipman and Taylor (1954), it appears that an upper layer of humus is present. Underlying this is an intermediate layer of loam, very porous material that is dark brown in color, which extends to a couple meters depth. This is underfoot by a unit referred to as bedrock that is a compact, fine-textured, almost pure calcium carbonate, which shows virtually no root structure. It is pure white, fairly soft," according to Lipman and Taylor (1934). Mayor describes the same material as coquina. According to Sacht (1954), Lipman and Shelley regard the intermediate layer as being an intermediate product in the decomposition of the bedrock, to form, with the addition of much humus, the surface layer of "fine textured, mellow, organic soil." The analysis of soil by Lipman and Taylor (1924) indicate that there are increasingly high percentages (from bedrock to soil) of Al, P, S, Na, and K compared to decreasing percentages of Ca and Mg, and little change in Si. They explain that aluminum silicate in the original rock undergoes decomposition through reaction with ammonia, formed from the decomposition of organic material or bird excreta, followed by removal of the ammonium silicate by leaching, while accumulating alumin in the soil. This would prevent silica accumulation. The authors explain the increased sodium, potassium and sulfur as resulting from the great absorptive capacity of the soil, differential leaching, and contribution from spray. Sacht suggests a 36-fold reduction in the weight of soil decomposed is required to yield the observed amount of alumin. Stone (1951) rejected this idea, as basal fragment are reported to be present on the reef. Sacht (1954) states that analyses may reflect contamination by decomposed pumice or basalt. Soils of small from Pisonia forest in the Marshall Islands led Stone to suggest that the bird excreta was stabilized by humus as it washed down through the soil, dissolving calcium phosphate. As the residual reaches the sands and rock below, the aqueous solution becomes alkaline and insoluble, precipitating out and cementing the loose material together. The acid solution dissolves calcium carbonate and replaces it with calcium phosphates, producing a hard pan, immediately below the humus layer. Hutchinson (1950) describes similar hardpan development on the atoll within the Line Island chain. These hardpans, however, do not have high alumin contents.

The high aluminum content and lack of hardpan is interpreted by Hutchinson (1950) as being significant. Hutchinson says, "It is plausible to suppose that the profile of Rose Atoll represents phosphatization due to concentration of phosphate in the parent rock, presumably with enrichment from bodies nesting in the trees, while the Palmyra profile represents a Pisonia stand growing on the site of a pre-existing guano deposit." Hutchinson points out that, in general, phosphates are better developed on dry equatorial islands than on wet ones. It is difficult to estimate the rainfall on Rose, since it is an uninhabited island. Records are available for Puka-Puka and Atollal, which probably reflect the conditions on Rose. Sacht reports 2 m of rain on Atollal as the yearly average (Seyler, 1943). On Puka-Puka the yearly totals for 1938-1942 range from 2.2 to 3.9 m. Sacht (1954) suggests, "Rose Atoll probably has a similar rainfall, although the number of rainy days may be great." These rainfall levels are significantly higher than those for the dry equatorial Line Islands (heating, this volume). The substantial rainfall could wash guano into the lagoon, in the manner suggested for Christmas Island by P. Heilbrin (personal communications, 1988) removing the surface phosphatic accumulations.

Hutchinson suggests, "the fertility of many wet atolls doubtless depends on such phosphatization, followed by bacterial nitrogen-fixation, as seems to be the case on Rose Atoll (Lipman and Taylor, 1924). Nitrite and nitrate producing bacteria are present in the soils. Their nitifying activity is more or less proportional to the amount of organic matter in the soil, according to Lipman and Taylor (1924)."
Volcanic Cones

Volcanic cones are relatively rare in American Samoa as opposed to Western Samoa. On Tutuila they are concentrated on the Leone Peninsula and the flank of the Taputapuau volcano (Fig. 16). A number of cones on Tutuila have been removed by long-term erosion. No crater lakes are present on Tutuila. One crater lake, Red Lake, is found on Amoud Island. Nyueta and Nuuiaielaie Islands west of Ofo are tuff cones. Cinder cones are present at Taupo Point on northwest tip of Ofo, and Lemaga Point on the southeast tip of Ofu. Eocene breccia core material makes up much of the A'aag FORMATION (Fig. 17). In addition, several large and small craters are present on the island of Ofu (Oliver and McCoy, 1968).

Coral Reefs in American Samoa

The coral reefs around Tutuila show considerable variation in distance to the shoreline and degree of development (Fig. 13). Mayor (1924) studied the structure and ecology of reefs around Tutuila. He suggested a drowned barrier reef 38 to 72 meters around Tutuila, forming a shell.

Daly (1924) suggests that the western part of the Tutuila shelf is 9-18 m less than the eastern part, and that the northern part is perhaps 9 m less than the southern part, with the old shelf being tilted toward the southeast.

Sandy Beaches of American Samoa

Sandy beaches are present in limited areas along the coastline of Tutuila. The abundance of sand seems to be directly related to the smaller number of coralite buildings present on this island. The sands occur as coarse sand and lithified beach rock. The sands vary from fine to medium and coarse grain. The sand commonly consists of fragments of coral, shells, and calcareous algae without silicious material. A few chitinous grains are commonly found. The sand generally has approximately equal amounts of high- and low-Mg calcite. The lithified sands commonly occur as lens-shaped bodies (now referred to as beach rock) which terminate in loose sands along the strike of the beach (Daly, 1924). The lithification is believed to result from cementation by calcium-rich fresh water percolating through the beach deposits which dip gently seaward (Daly, 1924).
HISTORIC VOLCANISM IN AMERICAN SAMOA

Manua

Thomson (1921) reports about Manua in 1866,

"a submarine eruption took place between the islands of Olooga and Tau, but few details have been recorded. Coleman Phillips states that on September 12, 1866, dense masses of smoke arose from the sea
and continued until the middle of November. The outbreak was preceded by repeated shocks of earthquake. Friedlander ascertained from an old inhabitant of the group that dense clouds of steam and water with sag and promile were ejected, and at night flames were plainly visible. Stewart's Handbook of the Pacific Islands gives the date as 1867, obviously in error, and mentions that the submarine volcano emitted forth rocks and mud to the height of 2,000 ft (600 m), killing the fish and discoloring the sea for miles (kms) around. The German Admiralitats Chart, according to Friedlander (1910), mentions a submarine volcano some 46 m below the water surface."

GEOLeOGIC MAPPING OF AMERICAN SAMOA

In Western Samoa hydrologists used physiographic features to map the geology. The strategy used was to map units using physiographic development in order to establish units of roughly equal age. In American Samoa Tutuila was mapped by a volcanologist, Harold Stearns, who coincidently was a specialist in geomorphic sources. Stearns carefully observed the geology of the American Samoa islands, identified the intrusive centers, calderas, and extracaldera lava flows. The relationships he observed allowed him to map volcanic centers. Often overlapping relationships allowed Stearns to establish relative ages for volcanism on an island. It was only after radiometric dating was attempted decades later that some absolute age relationships have been established.

Stearns (1944) concluded that Tutuila is built from five volcanic centers (Fig. 20). The volcanic centers are aligned on two or possibly three rifts, trending northeast-southwest. The majority of the lava are basic lavas, capped by limited trachyte, alluvium, coral reefs, and beach sands. Stearns suggests that the bulk of the volcanoes appear to be Pliocene, based on the weathered and eroded conditions. Fresh tuff cones and lava flows on the southwest side of the island, and on Tutuila Island are assigned Recent ages.
GEOLOGIC MAPPING UNITS

Masefau Dike Complex

On the north coast of Tutuila near Masefau village is a complex of hundreds of basaltic dikes ranging from a few centimeters to 1 meter in width. The dike rocks are vesicular and pearly; some are amygdaloidal. The dike complex strikes N70°E and dips slightly southward. These rocks are interpreted to be the oldest rocks exposed on the surface and were part of the deep structure of a volcanic rift zone.

The north side of the dike complex is exposed at Afafao Bay, in a cliff on the north side of a promontory opposite Bartlett Island (now called Nu'ustoga Island). Stearns (1944) suggests that the cliff may be an eroded fault scar or a sea cliff. Resting against the face of the cliff is tuff breccia overlain by 3-23 m of vitric tuffaceous pumice and tuff breccias on which aa-tuff cascaded over the cliff.

Stearns suggests the north side of the dike complex may be the eroded caldera wall of a volcano older than the Pago volcano, whose vent lies north along the present coast; alternately, it may be an eroded early rift zone horst block of the Pago volcano, later buried by flows. Based on analogies with dike complexes elsewhere, Stearns suggests that the complex was apparently formed not more than 140 or near less than 920 k below the surface of a rift zone and not 300 m or more of lava which formerly overlaid the dike complex have been removed by erosion.

The Masefau dike complex cut thin basaltic flows dipping at moderate angles (from 10° to 20° NW). These lavas are in large part shattered and brecciated by faults. Stearns suggests that much of the rock is the rift zone that shutters slowly, during repeated intrusion of the dike, and that the shattered brecciated material settled downward into the underlying magma chamber as breccia.

Otomoana Volcano

The Otomoana volcanic rocks are at least restricted olivine basalts. Stearns interpreted the outcrops as volcanoes on the northeast rift of the Afoafo Volcano during the closing phase of Pleistocene activity on the island. The Afoafo volcanic flows overlap the west slopes of the Otomoana volcanic cone. Thus it is suggested the volcanoes may have been essentially contemporaneous.

The lavas of the Otomoana volcanic center cover 2.1 square kilometers on the east end of Tutuila, surrounding Otomoana peak. Several intrusive olivine plugs, crater fills, and crater cones are exposed along the eastern coast. Cape Mataula is the largest intrusive plug. Flows are interbedded with augengranitized tuff beds. The ahu-lufuaha tradite plug cut these rocks. A large cinder cone can be seen partly exposed in the stream bed drainage to Tula.

Afoafo Volcano

The Afoafo volcanic center consists of thin bedded aa and pahoehoe flows, dikes, breccias, and tuffs exposed in a shield-shaped dome. The dome covers about 2.4 square kilometers on the east end of Pago Pago. The volcano is built over a rift zone trending northeast-southwest. The lava flows are thin bedded primitive olivine basalts, dipping 10° to 20° away from Afoafo village. A dike complex is exposed on the road southeast of Pago Pago village. Another 130 individual dikes are exposed in a promontory on the north side of Afoafo. Large numbers of dikes are also seen exposed south of Afoafo village. The rim of the caldera decreases in height rapidly to the southwest away from Afoafo and extends partially submerged offshore.

Pago Pago Volcano Series

The Pago volcanic series includes extra-caldera lavas, dikes, plugs, cinder cones, vitric and lithic tuffs, and breccias, as well as inner-caldera lavas, dikes, plugs, cones, tuffs, and breccias. The Pago volcano caldera was situated at the center of Tutuila Island. Stearns (1944) estimates that the caldera extended 9.6 km in length and 4.8 km in width.

Intra-Caldera Volcanic Units

Within the Pago caldera, lava flows formed thick ponded lava sequences to the north, east, and west. Pahoehoe flows are scarce. The lavas are generally aphric and olivine poor. Dikes are observed, ranging from 1 to 1.5 m wide.

The tuff and breccia members are the explosive debris that accumulated during the excavation of the inter-caldera
The deposits contain lithic, crystal lithic, and lithic debris. The beds range in texture from fine-grained, unsorted, grey tuffs to coarse blocky breccia 6 m thick with blocks of ejecta 1.5 m wide. Thick deposits of fire-fountain debris are interbedded with the beds of cataclysmic explosions. Plinianic beds are rare. A few beds of carbonaceous plant remains are occasionally found, which could be used to determine radiocarbon ages; the ages are less than roughly 40,000 years. Beds containing pumice fragments are also preserved. Other beds contain both basaltic pumice and dense fragments of tuff, indicating that the trachyte eruptions were followed by basaltic eruptions.

The beds are nearly horizontal near the source, where they have steep dips (reaching 32°) they interfinger and merge with talus breccia, suggesting the accumulated continuously with the talus at the foot of the caldera wall. An unconformity exists between the Pago tuffs and the pre-caldera lavas. The unconformity is well exposed in a small stream channel at the head of Pago Pago valley, where the caldera rim is seen. This banded olivine basalts are unconformably overlain by beds of talus breccia and tuffs.

Two dikes cut the lavas but do not cut the tuffs. Faulting is present but the lack of deformation of the tuffs suggests that the faulting motion pre-dates the accumulation of tuffs. The stream's channel, which is a series of cascades, cuts down through the exhumed caldera wall.

Another unconformity can be seen on the north side of Tautaua Peak. There, the massive columnar jointed pumiceous lava forms a peak resting on talus breccia, thin banded lithic tuffs, and basaltic pumice and cinder beds of the Pago Tuff Member. The intra-caldera lavas on the northeast side of the peak rest on red baked tuffic tuffs. The tuffs of the Pago volcanic series east of Tautaua Peak are underlain and overlain by massive pumiceous lavas.

A dike complex crops out in a valley on the northeast side of Tanapai Peak. The dikes are terminated by massive lavas, suggesting an unconformity or caldera wall between the caldera-forming lavas and the dike complex. A small spur of dense rock is present on the road just west of Aau. Stearns suggests it is a remnant of caldera lavas.

The Pago Caldera

Searns suggests the Pago caldera was 4.8 km wide and 9.6 km long. The geological evidence indicates the caldera formed by collapse following the building of a cone. A water development tunnel near Pago Pago Bay cuts a major fault. Along the fault a "groove and splinter" zone is observed 30 cm wide. There, 6 m of friction breccia is seen which contain faceted blocks up to 60 cm across and smaller fragments which have been ground to balls by friction.

The lavas inside and out of the caldera differ. Stearns suggests at least 480 m of collapse took place. Projections of the original height of the mountain, using the dip of extra-caldera lavas, indicate the mountain would rise 1200 m above present sea level, if the cone had the same slope as the summit. The southern rim of the volcano was much lower than the northern rim. Stearns suggests the caldera may have been horse-shoe shaped with no rim on the south.

Searns suggests, "by analogy with other similar basaltic volcanoes the collapse probably proceeded with the growth of the upper part of the cone, the caldera widening and deepening progressively even though lavas were erupted simultaneously on the floor. Subidence finally stopped as the volcano approached old age and the lavas began to differentiate. Filling gained on subsidence, and at the cessation of activity the caldera was filled to the brink in the northwest sector, overtopped and buried by perhaps as much as 250 m of lava in the southern and southeastern sectors, but lacked about 100 m of being filled in the northwestern sector."

Trachyte Plug

Several trachyte plugs and domes can be seen associated with the Pago volcano. The plug extends to the Ocean, which looms over Pago Pago Harbor. Some volcanic plugs, like Vatuia and Pioa, are so low that the upper bulbous parts of the domes remain. In other places, too much structure has been eroded that the remnants have a transitional appearance between domes and plugs.

The magnificent harbor of Pago Pago is dominated by the trachyte dome, called Pioa, or more commonly the Rainmaker. The Rainmaker is a trachyte dome 300 m wide, 720 m long and 515 m high. The landmark was described by Daly (1834) as reported by Stearns (1934), p. 1300-1301.

"A monstrosity litholite with quartz-poor and quartz-free phases in contact with basaltic flows on the north coast, but elsewhere with tuffs and breccias composed almost entirely of basaltic fragments but containing a few blocks of trachyte or rhyolite. He regarded the Pioa plug as an endogenous dome pushed through a funnel 1.25 mile (2 km) in diameter filled with explosion breccia. This is an excellent description of the mark except that the diameter of the funnel is less than half a mile (0.5 km) across and the breccia is almost entirely pre-funnel in age."

Searns suggests, "The trachyte evidently rose to a point nearly 900 ft (270 m) above sea level where it frothed violently producing red, white and black bimodal rich pumice and cinders about the vesicles, at the same time blasting out a few blocks of older basaltic tuff, breccia and lava. After a pumice cone formed with a crater had been
made, the pasty lava squeezed up and partly filled it... Columnar jointing developed at right angles to the base of the cooling lava.

A younger cone was built on slightly weathered tuff covering the floor of the Pago caldera, near the foot of the eastern wall. Thus, the Pioa eruption was a late event in the development of the Pago volcano. Stearns suggests the other trachyte plugs associated with the Pago caldera were formed in a similar way.

**Extra-Caldera Volcanics**

The extra-caldera volcanics include two units, the pre-caldera basalt and the post-caldera basalt. The pre-caldera lavas include flows, dikes and pyroclastics. The post-caldera lavas unconformably overlie the pre-caldera lavas, with only limited associated gravels and hillwash deposits observed. The best exposures of the extra-caldera rocks are seen along the nearly continuous sea cliffs of the north shore. Stearns mapped them from a boat. Many dikes and faults are exposed in the long keys that cut the volcano transversely. The widest dike is 18 m wide. At Point Nelson (now called Vai'a Point) a dike 9 m wide is seen not far below the level at which its lava erupted. (Stearns, 1944). These wide dikes are rare.

Pre-caldera olivine basalt, tuffs, and a dike complex and associated faults can be seen at Pagasa Bay. Thirty dikes cutting thin aa flows are exposed on the coast at the head of the bay. Sixty-eight dikes and several faults are exposed in the shore on the west side of the bay. The dikes are more numerous in the southeastern part of the bay. The number of dikes decrease however toward the promontory at the entrance to the bay. Stearns believes this is due to its location stratigraphically close to the original surface of the volcano.

Numerous faults are seen around the bay. Many are associated with breccias. Stearns reports many faults are

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**Figure 21. Illustration of the stages of geologic development of the island of Tutuila proposed by Stearns (1944).** Stage 1 (top) illustrates the general configuration of the island at the close of the shield-building volcanism. Stage 2 illustrates the configuration of the island at the end of subaerial volcanism. Stage 3 illustrates the configuration of Tutuila at the cessation of volcanism and beginning of stream erosion. Notice the absence of the Leone Peninsula in these figures by Stearns (1944).
The Tapatupe volcano is located on the western side of Tutuila Island. It is the southernmost volcanic center on Tutuila and is considered to be one of the oldest in the area. The Tapatupe volcano is characterized by its椭圆-shaped cone and its hydrothermal activities. The volcanic activity of Tapatupe has been studied extensively, and it is believed to be a hotspot for volcanic eruptions in the area.

The Tapatupe volcano is part of the larger volcanic chain that extends from the northeast to the southwest of the island. This volcanic chain is known as the Samoa Islands Volcanic Province and is one of the most active volcanic regions in the world. The Tapatupe volcano is located near the coast, and its volcanic activity has been monitored closely by scientists and tourists.

The Tapatupe volcano is a significant landmark for both local and international visitors. Its location near the coast makes it an easily accessible destination, and its scenic beauty and geological significance make it a popular destination for nature lovers and scientists alike.

In conclusion, the Tapatupe volcano is a unique and fascinating geological feature of Tutuila Island. Its location near the coast and its volcanic activity make it a significant landmark for both local and international visitors.
<table>
<thead>
<tr>
<th>Formation</th>
<th>Thickness</th>
<th>General description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recent Sedimentary</td>
<td>60 m</td>
<td>Brown, silt, poorly consolidated alluvium at the valley floors; coarse tills debris</td>
</tr>
<tr>
<td>Recent Lava volcanics</td>
<td>60 m</td>
<td>Olivine (pikettite) picritic basalt-buff spread from a fissure reaching Obstana Peak</td>
</tr>
<tr>
<td>Recent Aeolian tuff</td>
<td>200+</td>
<td>Lithic-rich tuff forming Aeolian Island.</td>
</tr>
<tr>
<td>Recent and Early Pliocene</td>
<td></td>
<td>Dense, jointed, coarse colored, trachyte, olivine, plagioclase, and coarse fiber glass</td>
</tr>
<tr>
<td>Tepotape volcanics</td>
<td>492 m</td>
<td>This bedded olivine basalt capped in place with a few somewhat thicker andesite-</td>
</tr>
<tr>
<td>Pago intra-caldera volcanics</td>
<td>321 m</td>
<td>The lower member is composed of thin-bedded primitive olivine basalt, associated</td>
</tr>
<tr>
<td>Pago intra-caldera volcanics</td>
<td></td>
<td>Massive aphanitic porphyric basalt and andesite lava flows, and clinker cones,</td>
</tr>
<tr>
<td>Alifuw volcanics</td>
<td>562 m</td>
<td>A shield-shaped dome built over a N 70° E trending rift zone and composed almost</td>
</tr>
<tr>
<td>Oolomea volcano</td>
<td>322 m</td>
<td>Composed largely of olivine basalt but capped with andesite basalt and porphyric</td>
</tr>
<tr>
<td>Emuheit (?) Unconformity</td>
<td></td>
<td>Thin basaltic flows dipping 10 to 30° NW cut by hundreds of basaltic dikes 1 to 2 m</td>
</tr>
</tbody>
</table>

![Table 1: Rock Units of American Samoa (from Stearns, 1944, Table 1).](image)
Paleomagnetism

Paleomagnetic studies of lavas from Samoa were first carried out by Tarling (1962, 1965). These early studies showed that normal polarity is present on Savaii. On the islands of Tutuila and Upolu, the stratigraphically higher units are normal polarity and the stratigraphically lower units are reversed polarity. Tarling compared the results directly with the Hawaiian Islands and concluded the rocks sampled did not exceed 2.5 million years in age. Furthermore, he suggests the overall migration of volcanic activity from East to West is at an average rate not less than 7.7 cm/kyr and probably similar to the migration rate of 10 cm/kyr observed in Hawaii (McDougall, 1966).

More recent paleomagnetic studies have been conducted by Keating and Tarling. Care was taken to collect the freshest outcrops, often along the shoreline, in order to avoid the problems of secondary overprints experienced by Tarling (1965). In general, the sampling was very successful and well-defined paleomagnetic directions resulted from the work. The poles from the island of Savaii fall into seven groups (Keating, 1985a). With few exceptions, each of the volcanic units of Savaii yields a tight cluster of paleomagnetic directions; the sites do not appear to display substantial rotation and all appear to be normally magnetized. The mean site direction; are plotted in Figure 22 using the geologic names for volcanic units mapped by Kear and Wood (1929). While a few sites appear to be incorrectly assigned to younger mapping units (Keating, 1985a) most

Figure 22. Mean site directions for paleomagnetic sites from the island of Savaii. The site directions from individual volcanic "formations" appear to occur in three clusters. The oval of confidence have been omitted for clarity. The α95 is less than 2° for most mean site determinations.

<table>
<thead>
<tr>
<th>Island</th>
<th>Observer</th>
<th>Comparable to</th>
<th>Inferred Age</th>
<th>Observed age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Savaii</td>
<td>Thomson</td>
<td>Hawaii</td>
<td>0.1</td>
<td>0.0-0.45</td>
</tr>
<tr>
<td>Savaii</td>
<td>Dana</td>
<td>Manua Kea</td>
<td>0.4</td>
<td>0.4-0.6</td>
</tr>
<tr>
<td>Upolu</td>
<td>Thomson</td>
<td>Maui</td>
<td>1.4</td>
<td>1.53</td>
</tr>
<tr>
<td>Upolu</td>
<td>Dana</td>
<td>Kauai</td>
<td>0.3</td>
<td>1.2-2.5</td>
</tr>
<tr>
<td>Tutuila</td>
<td>Thomson</td>
<td>Oahu</td>
<td>1.3</td>
<td>3.8-15</td>
</tr>
<tr>
<td>Manua</td>
<td>McDougall</td>
<td>Hawaii</td>
<td>0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 3. Age comparison between Samoan and Hawaiian islands.
On Savaii, the rock units are all normally magnetized (Fig. 23) and display a systematic change in inclination. The oldest (stratigraphically lowest) units have the highest inclinations, intermediate units have moderate inclinations, and the youngest (stratigraphically highest) units have the shallowest inclinations. Because the paleoinclinations from these various rock units fall into these groupings, it would appear that at least three major volcanic episodes are present on Savaii.

A comparison of the paleomagnetic results from rock units mapped using the same geologic names proposed by Kear and Wood (1959) indicates that the use of the same names on both islands is incorrect (Keating, 1985a). Units sampled on Savaii have normal polarity (Fig. 24) whereas on Upolu these units have reverse polarity (Tarling, 1965). The paleomagnetic results show that volcanism is not wholly contemporaneous on these islands. A revision of the geologic mapping on these islands would be very useful.

Mixed polarity was found on the island of Upolu (Fig. 23). It appears that the rock units of western Upolu are characterized by normal polarity while the stratigraphically lower units on eastern Upolu are reversely magnetized.

Figure 23. Maps of the main islands of the Samoan chain illustrating the magnetic polarity of sites studied by Keating and Tarling and summarized in Keating (1985a). (N = Normal polarity; R = reversed polarity; T = transitional) directions of undetermined polarity, M = both normal and reversed polarity magnetization is present in the lavas and dikes at these sites). The kilometer scale refers only to the island of Tutuala.
petrography and Isotope Geochemistry

Western Samoa

Petrographic studies of rocks from Samoa are numerous. The descriptions of volcanic units from Western Samoa used in Keair and Wood (1959) were made by a petrologist, R.N. Brothers. Similarly, petrographic descriptions for volcanic units in American Samoa made by G. Macdonald were included with the geologic descriptions of H. Stearns (1944) and a later publication by Macdonald (1968). Many of the early detailed descriptions of the rocks from Samoa were made at the time of the volcanic eruptions early in the century. Mohle (1902) also described rocks collected from Upolu, Savaii, Apolima and Fanuatapu Islands. Kaider (1904) as well as Wegener (1902, 1903a,b) described rock from the 1902 lavas of Maua Afi, Savaii. Rocks from the 1905 Matavatu lava flow were analyzed by Heuseler and described by Klautsch (1907). The 1905 flow was also described by Jensen (1907). Analysis of Matavatu lavas (Jenzen, 1908) differed somewhat from those of Heuseler, reported by Keair and Wood (1929). Other descriptions of the Matavatu eruption and its lavas, are reported by Angererheiner (1905), Grevel (1911), von Bulow (1906), Friederici (1910), Reinecke (1905, 1906), Sapper (1906, 1909, 1911a, 1911b, 1912, 1915), and Schmidtman (1911).

Friedlande (1910) examined the rift zones of Savaii and his collection of rocks was subsequently examined by Weber (1909) and reviewed by Macdonald (1944). Thompson (1921) summarized previous rock descriptions. Bartram (1927) described the petrology of rocks collected by members of the New Zealand Geological Survey and included a few analyses by F.T. Seelye.

Hedge and others (1972) analyzed the major element chemistry and the minor elements Rb, Sr and Ni. The basalts yielded the highest leaching FeO/Fe2O3 ratios found from ocean basins. They concluded the high potash content and high Sr ratios suggest that these rocks from Upolu and Savaii were derived from a mantle source which was less depleted by previous magmatism than much of the sub-oceanic mantle.

American Samoa

Friedlande (1907) produced an early account of the geology of Samoa, which included petrographic descriptions by Weber. Comparisons are made with rocks collected from American Samoa by Daly (1924). Stearns (1944) describes the geology of American Samoa, including petrographic descriptions by Macdonald (1944) of Tutula (American Samoa), Upolo, and Savaii (Western Samoa). Macdonald (1966) describes petrographic analyses of rocks from Tutula and the Manu’a group. Macdonald concluded that the "differentiation trend of Samoan rocks" for the most part closely parallels that of the Hawaiian alkali suite.
Where the silica ratios lie very close to the boundary be-
tween the tholeiitic and alkaline fields (Upton and
Wadsworth, 1965) with some rocks on each side of it.
Slice and McCloy (1968) discuss the geology of the
Manua islands, with Slice (1968) reporting the major
element petrology. Hubbard (1978) outlines rocks from Slice
(1968) and reports that lavas from the Manua islands are
typical oceanic island alkali lavas; and also reports the rare
earth abundances. He suggests the lavas were segregated
from a normal oceanic upper mantle at greater than 40 km
depth.

Dredged Rocks

Hawkins and Natland (1975) examined the major ele-
ment chemistry and trace element geochemistry of rocks
dredged from the flanks of Savaii, Upolu, and Tutuala as well
as nearby seamounts (including Mechias) within the
Samoa seamount chain. The post-eruption lavas sampled
are strongly undersaturated with silica. In order to explain
the Si and Al-poor, and Ca, Ti, Mg, Fe-rich basanites and
olivine nephelinites, the authors suggest that magma
generation took place close to the probable base of the
lithosphere. Magma generation was due to moderately
extensive melting (15-15%) of an essentially anhydrous and
alkali-poor mantle at depths of about 85 km. Hawkins and
Natland suggest a hot spot mechanism is uncertain and a
more likely explanation is a combination of viscous shear
melting and lithosphere delamination due to the deformation
of the Pacific plate at the nearby Tonga Trench subduction
zone.

Natland (1980) suggests that at a magmatic lineage can be
identified on Mathias Seamount producing trachytes and
phonolites. Natland suggests the compositional differ-
ences observed result from differences in the extent and
depth of melting of the lavas. All Samoa lavas were found
to have an undepleted radiogenic mantle source. The post-
eruption lavas have higher 87Sr/86Sr and Rb/Sr ratios and a
lower K/Rb ratio than shield basalts. Natland suggests the
chemistry is indicative of thermal-convective disturbances
in the mantle, caused by deformation of the Pacific plate
where the Tonga Trench intercepts the plate in the vicinity
of the Samoa chain.

Source Material

Natland and Turner (1985) reported on the petrology
of lavas from American Samoa and Western Samoa. They
suggest the shield volcanoes evolved from a dominantly
tholeiitic stage to a transitional stage with tholeiitic and
alkaline basalts interbedded, to a dominantly alkaline stage.
The Samoa lava, including the tholeiites, are enriched in
alkalis and TiO2. Trace element geochemistry indicates that
mantle sources are less depleted than those in Hawaiian
volcanoes. The mantle sources of Samoa basalts on each
island are less depleted sources, tapped through time. This
pattern of depletion is the opposite sequence from that
observed on any Hawaiian volcanoes. Natland and Turner
suggest a pronounced lateral isotopic heterogeneity
beneath the island chain gives rise to the trace-element
compositions observed in the post-eruption lavas.

White and Hofmann (1982) examined the Sr and Nd
isotope geochemistry of lavas from Samoa. They concluded
that these ratios from Tutuala and Upolu diverge significantly
from the mantle array (Davies, 1981). (The results from the
Manua islands, at the eastern end of the chain plot within
the mantle array). The results cannot be explained by bi-
ary mixing of depleted and undepleted mantle reservoirs
or by variable magmatic depletion of a planetary reservoir.
White and Hofmann (1982) suggest reinjection of crustal
material into the mantle. Newman and others (1984), how-
ever, point out that this recycling model is difficult to reconc-
ile with values of 4He/3He which are 18 times atmospheric
(Rison and Craig, 1982). Newman and others suggest that
deviations in 87Sr/86Sr - 87Sr/86Sr correlations exist in
Samoa. These could be due to modification of the mantle
source or by a significant residence time at depth prior to
eruption.

Matuda and others (1984) examined Sr isotope from
Samoa rocks, and concluded that the correlation in
87Sr/86Sr and Rb/Sr ratios reflect multi-component
mixing. They concluded mantle heterogeneity exists over a
large scale within the south Pacific.

Wright and White (1987) examined Sr, Nd, and Pb
isotope ratios and daughter element concentrations from
highly undersaturated post-eruional lavas erupted in
Recent to Historic time. They suggest the post-eruional
lavas are derived from mixtures of the shield-building
volcano source and a post-eruional volcanic source which
is characterized by high 238/235U-Pb, 143Nd/144Nd and low
206Pb/204Pb and 143Nd/144Nd ratios. They conclude the
source of the post-eruional volcanics contains recycled
ancient sediment.

Studies of two types of xenoliths from Samoa post-
eruional lavas are reported by Wright (1987). Wright con-
cludes the xenoliths were probably formed during diapirism
associated with the melting which produced the Samoa
shield volcanoes (1-2 Ma) before their eruption as part of the
post-eruional lava flows.

The studies of the isotopic composition of rocks from
Samoa has contributed to a better understanding of the
crater of the earth's mantle. Stromatolite, Nd and Pb isotopic
abundance data shows that important isotopic mantle
anomalies exist (Hart, 1984, Dupe and Allegre, 1983). The
isotopic anomalies require a mantle source which may con-
tain recycled ancient sediments (Wright and White,
1986). Arguments have been made for a compositionally
layered mantle or a heterogeneous mantle mixed by large


Zindler and Hart (1986) conclude that the evidence for chemically heterogeneous mantle is today, unequivocal. Arguments continue however about the nature, development, and scale of the heterogeneity. Most authors agree that the heterogeneities are long-lived, being preserved in the mantle for times of approximately 1-4 AE (DePaolo and Wasserburg, 1976). Seismic tomography studies (Dziewonski and Anderson, 1981 and 1983; Dziewonski, 1984; Morelli and Dziewonski, 1987; Dowben and Hilton, 1989) indicate the heterogeneity is large scale. The isotopic studies of rocks from Samoa summarized here have played an important part in developing new models of the earth's mantle.

Radiometric Age Dating

Radiometric age dates for the Samoan Islands were summarized by Keating (1987). By combining the radiometric results from the Samoan Islands with those from the seamounts and banks of the Melanesian Borderland (Duncan, 1985), a progression in volcanism is observed. A comparison of ages for the Samoan chain and the Hawaiian chain (Fig. 25), shows a progression in ages along the chain.

A comprehensive summary of the radiometric ages for Tutuila, American Samoa has been made by McDougall (1985). McDougall reports that the subaerial portion of the Pago shield volcano was constructed between 1.24 and 1.28 Ma. The Pago caldera was formed at roughly 1.27 ± 0.02 Ma. The emplacement of trachyte bodies occurred at 1.3 ± 0.01 Ma. The Olomoana and Taputapu volcanoes formed over the same interval as the Pago volcanism. McDougall (1985) suggests that the rate of migration within the island chain is about 9 cm/yr. Modern post-errosional volcanism is present on the main Samoan Islands and yields ages less than 1 Ma.

Naitland and Turner (1985) published radiometric dates for the subaerial portion of the Fagafaoa shield volcano in Western Samoa, and suggests it was active between 2.7 and 1.5 Ma as well as several dates from Tutuila.

Hydrology

Water stored within rocks is a valuable resource. The water is derived from precipitation. Some of the rainfall water evaporates from the land surface and returns to the atmosphere; some is utilized in transpiration by plants and also returns to the atmosphere; most of the rain water either runs off the land in streams and eventually is discharged to the sea or is absorbed into the soil or rocks and becomes ground water recharge. Water that percolates past the root zones of plants descends to a level where the voids in the rocks are filled with water; this is referred to as ground water. The upper surface of the water is referred to as the main "water table." The water table slopes gradually from the interior of the island to near sea level at the coast (Fig. 26). Where sufficient fractures or cavities exist near the coast line, springs and fresh water ponds exist. The ground water escapes to the sea at a relatively constant rate. At times of drought, the water table may drop below the base of a stream or pond. As a result, surface water may dry up. The
However, it is not always a zone of mixing is present in which the water is not desirable for human consumption. Tidal flushing at the coast line, particularly where permeable rocks are present, influences the size of the zone of mixing.

Discussion of the Hydrology of American Samoa

Eyre (1950) and Stearns (1941) and Boneley (1975) separate rock units into older volcanics (equivalent to shield-building lavas described by other authors), younger volcanics of the Leone plain (which are equivalent to post-caldera lavas as observed in Hawaii) and alluvium. The young, post-caldera lavas are the most permeable, resulting in yields of up to 300 gallons per minute to most wells with little drawdown of the water table. By contrast, the permeability of the alluvium and older volcanics is highly variable. Much of the intracaldera volcanics are not productive aquifers while any particular flow unit can have high permeability, it is generally of limited areal extent that the unit overall has generally low permeability (Fig. 28). Locally, productive aquifers have been discovered in the intercaldera volcanics. These aquifers are associated with fractures, faults, occurrences of volcanic ejecta, and permeable contacts between separate flow units. These zones may sustain yields to a well of 200 gallons per minute or more. However, if such a yield in excess of surrounding ground water recharge rates, water levels will steadily decline and salt water intrusion will eventually ensue (P. Eyre, personal communication, 1990).

Eyre (personal communications, 1990) states that "even the flank flows of the older volcanoes may provide aquifers of only limited productivity, relative to the post-caldera lavas of the Leone plain, because they are frequently dense

![Image of the main water table and perched water table. (Figure modified from MacDonald and Abbott, 1970)](image)

![Image of the relationship between the fresh water aquifer and the underlying salt water observed in volcanic islands. Areas of dike-impounded waters are also illustrated. (Figure modified from MacDonald and Abbott, 1970.)](image)
and thick bedded and of limited areal extent. This may be explained by the predominance of viscous alkalic basalt and andesite in Samoa, as well as by the compactness and intensity of erosion activity on this small island. *Eyre also states that the poor performance of many wells drilled in the older volcanics attests to the difficulty of finding good aquifers.*

The older volcanics do become an important water supply at high elevations where gravity flow is stopped by dikes, or near sea level where tufts and alluvium can be a cap rock which prevents discharge to the sea (Stearns, 1944).

Unweathered tufts are characterized by moderate permeability. Weathered tufts are often impervious. Breccia tends to be dense and have low permeability, when weathered. Fresh clinders have high permeability. Weathered clinders have low permeability. Dikes, interbedded tuffs, and breccia reduce the effective areal extent of lava flows, having a profound effect on ground water movement.

Post-Eruption Volcanics - Leone Peninsula

The eruption of post-eruptional volcanics in American Samoa was voluminous and intense. Major centers include the craters of Fagatolo, Fagauma, Olofuu, and the craters near Olofou Peak (P. Eyre, personal communication, 1990). These eruptions produced several areally extensive flows; most are permeable. A large part of the flows cover existing coasts and reefs. The Leone peninsula is a major geographic feature (Fig. 16) formed as the flows built out 3.2 km from the former coastline. Ground water recharge to the lavas of the Leone plain is derived from mountain stream flow as well as direct infiltration of rainfall.

Thus, the Leone peninsula is the major aquifer supplying dependable water for Tutuila. Because saltwater underlies the freshwater at a relatively shallow depth, excessive pumping can cause saltwater intrusion when wells reach more than 6 to 9 m below sea level (Stearns, 1944; Davis, 1963; Bentley, 1975; P. Eyre, personal communication, 1990).

Wells drilled deeper than 18 m below seawater should yield salt water (Bentley, 1975). Saltwater intrusion has caused wells to be shut off during drought years, resulting in water shortages and rationing. Salt water intrusion is exacerbated by the close spacing of wells.

Eyre (personal communication, 1990) estimates that 25 million gallons per day (Mgal/d or 1 m³/s) of ground water recharges Leone peninsula. Most of the runoff from the mountains adjacent to the plain appears to infiltrate the aquifer, and very little appears to reach the ocean as surface runoff.

Bentley (1975) reviews drillers' logs for wells in the Leone peninsula. The logs indicate that the dense interior portion of lava flow forming the volcanic peninsula is 15 to 9-15 ft thick. The well logs show little uniformity from one well to another, other than the presence of alternating layers of hard basalt and softer units of ash, rubble, and fractured rock. One well at Fiafia drilled through two hard basalt units (29 m and 10 m thick) which were separated by soft material (7 m thick), interpreted as tuff.

Eyre (personal communication, 1990) reports that springs issue at high elevations from the Flagi Pago volcano into Taumau Stream in Mormon Valley. The mapping of dikes in the area by Stearns (1944) suggests that high level dike water may occur here. Logs from wells drilled on the floor of Mormon Valley indicate the original valley was filled by Leone volcanics overlying the weathered surface of the older volcanics. The older volcanics have an "impermeable weathered surface," which prevents the water to several tens of feet above sea level. As the weathered slope dips seaward beneath the Leone plain, saltwater support; the bottom of the freshwater lens is in accordance with the Ghayen-Heinrich principles. Bentley (1975) mentions that reports by consultants (Austin, Smith, and associates, 1963 and 1972) suggest that waters are present.
Stearns (1942) reports that the Navel Station in Pago Pago had for years used water from the Pago reservoir near the head of Fagafisia Valley. Stearns found that the reservoir was fed by a spring 4 m above the top of the dam in the head of the reservoir (234 m above sea level). The reservoir is situated in atra-caldera volcanics according to Stearn's 1944 geologic map, below the steep sides of the Matafao trachyte plug. The spring that feeds the Pago reservoir issues from the fault associated with the Matafao plug.

The region from Vaisale to Fagafisia has no developed ground-water resources (P. Eyre, personal communication, 1993). Outcrops of a flows with alternating layers of high and low permeability are exposed in the walls of several valleys. Exploration for ground water may prove fruitful in such areas. Several wells have been drilled into the alluvium in the Pago Pago harbor area. These shallow wells yielded fresh water at modest rates, but the wells are susceptible to pollution, and have not been put into production. A private well drilled at the south end of the head of Pago Harbor tapped a thick zone of fresh water under estuarine-precipice deep in the atra-caldera volcanics (P. Eyre, personal communication, 1992). This successful well shows the benefits possible from atra-caldera aquifers which exist deep in the older volcanics.

At Utulei, a productive well was dug into coastal sediments, 4 m deep (Bosley, 1974) and only 35 m from the shore. The well is in filled marshland, and appears to tap an artesian discharge from underlying atra-caldera volcanics. There is insufficient surface runoff or rainfall in this area to supply the flow from the well and chloride concentrations increase only slightly during drought (P. Eyre personal communication, 1990).

A well in Aua also tapped an artesian aquifer deep in the atra-caldera volcanics. However, the well was overpumped and its water became salty. Sparse data from a shallow well on the valley floor indicates that, similar to Utulei, water discharges from the older volcanics into the valley floor sediments.

The lower sediments of most stream valleys in Samoa contain thick deposits of alluvium. Often the alluvium contains clay which is impervious and trap water behind coastal alluvium. Shallow wells dug into these deposits are common and produce brackish water suitable for bathing and laundry. Wells in the alluvium are present in Fagafisia, Pago Pago, Aua, Avea, Alofaa, Aoaulau, and Tula (Bosley, 1975).

In eastern Tutulua from Laualatua to Tule the "drainage basins are small and rugged, most wells have low capacity and deliver brackish water." (P. Eyre, personal communications, 1990).

In west and north Tutulua, no wells have been drilled because the stream flow is adequate for the population. The geology is favorable for ground water. A flows are common in flank flows on the Olocomoa, Alofaa and Pago Pago volcanic flows. These flows form sequences of denselayers alternating with permeable, interflow layers. The calderas area is also large, therefore, important aquifers are likely (P. Eyre, personal communication, 1990).

Analyses of water samples reported by Bosley (1979) indicate that the waters from volcanic rocks and alluvium show low concentrations of dissolved solids, except those samples from deep wells and wells near the coast which show effects of salt water intrusion. Chloride concentrations ranging from 7 to 1,200 mg/L during 1975 to 1983 have been reported by the U.S. Geological Survey (Yes, 1987; Yes, 1985). A level of less than 250 mg/L is the recommended limit for drinking water by the U.S. Environmental Protection Agency (1982).

In modern times, American Samoa has experienced droughts, which have greatly reduced the surface water supplies. In the 1970's, water rationing programs were necessary, and the operations of two pumped canneries were interrupted (Masouka, 1978). During the 1980's, powerful hurricanes have hit both American Samoa and Western Samoa, contaminating surface water sources. In addition, frequent landslides occur in these islands (Buchanan-Banks, 1991), which fill and destroy surface water supplies and reservoirs (Stearns, 1941). Further development of ground-water supplies are needed to meet the needs of the populations of American Samoa and Western Samoa.

Soils in American Samoa

Wingert (1983) describes the soil formations designated in American Samoa. The basic igneous rocks weather to form clayey soils which are nearly impervious. The volcanic ash and cinders weather to sandy soils. Colliuvium forms at the base of the steeper slopes, consisting of silty clay, clay loam, and silty clay. It is poorly sorted, containing large boulders, and gravel, which constitute up to 35% of the material. Alluvium is deposited by water and ranges from silty clay to fine sand. Thirty soils have been mapped in American Samoa.

Geologic Development of the Samoan Island Chain

In discussing the stages of Hawaiian volcanism, Macdonald and Abbott (1970) state that "volcanoes, like people, pass through a succession of stages in their development." Stearns (1946) outlined eight stages of volcanism (Fig. 26). Macdonald and Abbott (1970) outline nine stages (Fig. 30). The models are similar and outline a history in which the volcanoes built from the sea floor in a phase referred to as the youthful stage (Macdonald and Abbott, 1970) on the shield-building phase (Stages 1-3, Fig. 30). Most of the volcanos are formed during this shield-building phase. The next phase of development is referred to as
Figure 29. Stages of volcanism proposed by Stearns (1946).
the mature stage (Macdonald and Abbott, 1970). Stearns (1946) suggests the formation and collapse of the calderas characterizes the end of this major episode in the development (Stages 4-5), followed by trachytic intrusions and formation of abundant cinder cones (Stage 5). An extensive period of erosion follows (Stage 6). Coral reefs form on the slopes of the volcanoes during the erosional phase (Stages 7 and 8). Late in the history of the volcano, post-erosional volcanism occurs, often concentrated on the slopes of the volcanoes rather than concentrating in the caldera area (Stage 8). This is referred to as the old age phase by Macdonald and Abbott (1970). The volcano continues to subside throughout its history, eventually sinking below sea level until coral reefs grow to form an atoll.

**Samoan volcanic development**

**Shield-Building Phase and Caldera Collapse**

The shield building phase of volcanism on Upolu is represented by the Fagatolo volcanics. Kear and Wood (1959) and Kear (1967) suggest the Fagatolo volcanics include two somewhat differently weathered landforms. Talling (1966) found that the Fagatolo volcanics in western Upolu were normally magnetized while those in eastern Upolu were dominantly reversely magnetized. The paleomagnetic data verifies the Kear and Wood (1959) and Kear (1967) notions that the Fagatolo Volcanics could be divided into an upper and lower series.

Nastland and Turner (1965) argue that Fagatolo Bay on Upolu represents the collapsed caldera of the Fagatolo Volcano. They argue that the more alkaline basalts and all of the silica differentiates are centered on Fagatolo Bay. Nastland and Turner (1980) however point out that the difference between tholeiites and alkaline basalts in Samoa is arguable. In the case of Samoa, the influence of mantle sources is important, "since they very probably have enhanced the alkalicity of all Samoan basaltic lavas compared with those of Hawaii." As one reviewer pointed out, "alkalicy and silica saturation are not completely interchangeable concepts," according to Nastland and Turner (1980).
Regardless of the petrologic arguments, Natland and Turner make a strong case for the existence of a caldera at Fagamoa Bay but acknowledge the lack of "the critical evidence of a ring fault." More mapping is needed in order to verify the geologic relationships and verify the existence of the proposed caldera on Upolu.

On Tutuila, the dikses of Masefau Bay, and the Pago, Apol, Oloamoana, and Tapatupu volcanic series represent the shield-building lavas. These four volcanoes formed nearly contemporaneously at about 1.4 Ma. Pago Pago Harbor marks the center of the collapsed Pago caldera.

On Savai, the oldest exposed volcanics are the Salani volcanics. The island of Savai is thickly mantled by post-erotional rocks, leading most geologist to believe that the shield-building stage of volcanism is buried by later volcanic units on this island. Recently a SeabMARC II side-scan sonar survey was made on the southern flank of Savaii (Figs. 31-34). Despite surveying areas of the flank down slope from extensive cinder cones, little indication of young volcanism is present. The talus-covered slopes appear consistent with the view that the base of Savai is indeed old and that the younger volcanics have buried the older shield building volcanics. Stice and McCoy (personal communications, 1990) point out that this appears to be the case on Olo, Oloenga and Tua based upon their work in the islands (Stice and McCoy, 1960).

Post-calders Stage Volcanism
Post-caldera stage volcanism is clearly present on Upolu and Tutuila. Trachyte plugs and numerous cinder cones are evident, along the axis of both islands.

First Erosional Stage
Upolu and Tutuila have experienced considerable erosion. Both islands display extensive dissection by streams.

Post-erotional Volcanism
On Upolu, the Salani volcanics represent post-erotional volcanism. The lavas fill pre-existing valleys. On Tutuila, post-erotional volcanism built the Leouo peninsula. The Astore tuff covered parts of Tutuila, Olo and Tau Islands.

Second Erosional Phase
A second erosional phase is evident in Western Samoa. On Upolu, the surface of the Salani volcanics are deeply weathered and deep soils have formed. Deep-canyons cut the post-erional Salani volcanics indicating a long period of erosion took place. On Savaii, the Salani volcanics are moderately weathered and a thick soil cover is present. Numerous deep incised rivers drain these volcanics.

On Tutuila, the youngest of the high volcanic islands in the chain, the post-erotional volcanics which form the Leone peninsula show little evidence of erosion.

Reef Growth Stage
Reefs are present around Upolu, Savaii, Upolu, Tutuila, Olo, Oloenga and Tua to varying extents. Many reefs have been buried by lava flows. The coral reefs in the Savaii chain have probably not fully recovered from the oscillations of sea level associated with the ice ages. The plantation of the flanks of the volcanoes by wave action has provided a stable base for the reefs to grow. Barrier reefs are present where stable platforms remain on the slopes of the islands. Mass wasting of the flanks of the islands, particularly on Savaii, however, has contributed to the loss of coral reefs on the flanks of the volcanoes as portions of the volcanoes slump toward the sea floor.

Continued Volcanic Rejuvenation
On the islands of Savaii and Upolu, volcanic activity has continued until Recent times. On both islands, the relatively unweathered lavas (from the Aopua, PuaPua and Lefaga volcanics) are widely distributed (Fig. 7). Historic volcanism has covered much of Savaii. The volcanic activity on these islands has been repeatedly rejuvenated, producing the Lefaga volcanics, then the PuaPua volcanics, and finally the Aopua volcanics, as well as submarine volcanism near Manu'a.

Western Samoa lies just north of the Tonga Trench (Fig. 35). Hawkins and Natland (1975) and Natland (1980) suggest that plate bending associated with subduction of the Pacific Plate in the Tonga Trench is responsible for the rejuvenated (post-erional) volcanism so common in Western Samoa. Natland (1980) suggests shear-melting beneath a zone of lithospheric diatation is responsible for the continued volcanism found in Western Samoa.

Petrogenesis of the Samoan Lavas
Three manuscripts (Hawkins and Natland, 1975; Natland, 1980; and Natland and Turner, 1985) compare the petrologic development of the Samoan volcanic chain to that of the Hawaiian chain. The recent studies of the isotope geochemistry indicate that the mantle geochemistry under the Samoan chain is anomalous. The mantle geochemistry complicates the general interpretation of tholeiitic, transitional, and alkalic volcanism. Samoan lavas have probably all been enhanced in alkalinity compared with Hawaiian lavas. As stated previously, "the alkalinity and degree of silica saturation are not completely inter- changeable concepts." Despite the problems produced by enhanced alkalinity, Natland and Turner (1980) believe that "ranges in basalt composition exist encompassing at least the Samoan equivalent of the tholeiite-alkalic basalt transi-
Figure 31. Map showing the location of the SeaMARC II side-scan sonar survey conducted south and west of the island of Savaii, Western Samoa. The side-scan sonar images are shown in three segments (Figs. 32-34).

Figure 32. SeaMARC II side-scan sonar image of a seamount immediately west of Savaii. The seamount is capped by low reflectivity material, probably sediments, which appears white in the image. Several faults that parallel the trend of the island chain can be seen on the sea floor east of the seamount. Four small cones can be identified in the image.
Figure 33. StabMARC II side-scan sonar image of the western and southwestern flank of Savaii. The survey was conducted to determine if extrusive volcanism had occurred along the submarine extensions of the volcanic rift zones (shown in Fig. 6). Only isolated small volcanic cones are seen. The cones are not aligned along extensions of the rift zones but instead occur at the edge of the side-scan image on the southwest flank of the island. The flanks are dominated by slump and debris flows.
WESTERN SAMOA

Figure 34. SeaMARC II side-scan sonar survey of the southern flank of the island of Savaii. A large submarine platform extends southward of Savaii (shown along the right side of this image). Dark lineations along the edge of this platform mark edge of submerged reef terraces. A cluster of small volcanic cones occurs at the southern extension of this platform and is likely to be the submarine extension of the volcanic rift zone (shown in Fig. 6). The platform is covered by low reflectivity material (which appears white in this image) and is probably reef debris and carbonate sediments. The southern flank of Savaii (left side of image) is dominated by high reflectivity (volcanic?) debris flows, which appear black in these images.
tion. As in the Hawaiian case, this represents a temporal succession, but unlike Hawaii, the transition is from more to 'less depleted compositions through time.' Readers desiring more information of these petrologic arguments are referred to the references previously cited.

THE CORAL REEF PROBLEM

In the early 1800's the descriptions of atolls as great rings of coral around calm lagoons, within the deep Pacific, captured the interest of many. Charles Lyell (who was mentor to Charles Darwin) suggested the atolls were the crests of submarine volcanoes overgrown by coral (Darwin, 1843). Darwin conceived the idea that volcanoes grow from the sea floor, form high volcanic islands, then die, subsiding into the sea. Corals grow on the shorelines imnming the volcanic islands; as the volcanoes subside, the corals grow upward, leaving a gap between the barrier reef and the central volcanic island. As subsidence continues and the volcano subsides below sea level, the coral atoll remains. Darwin used direct observations from the fouling of ship bottoms to estimate coral growth rates, concluding corals would have no difficulty in growing fast enough to keep up with subsidence. Darwin's observations were followed by those of James Dana (1875), whose book "Corals and Coral Islands," increased the acceptance of Darwin's ideas on island subsidence.

As a consequence of the Challenger Expedition, John Murray rejected the subsidence hypothesis (Menard, 1986). As a result of the Challenger Expedition, Murray
was aware of the deep sea sedimentation of skeletons of microorganisms in the sea. He concluded that reefs formed because sediments accumulated on the summit of seamounts, eventually producing shallow banks from which corals could grow. The Murray hypothesis gained considerable support in the late 1980s. Public interest in the Challenger Expedition contributed to the favorable reception of Murray's hypothesis. Darwin's reaction to the hypothesis was that he would like to see some " doubly rich" millionaires " pay for boring of reefs to test the hypothesis. The text by Stoddart (this volume) outlines the results of the scientific drilling of reefs, including the early drilling by the Royal Society of London on Funafuti, Atoll. Because the early drilling did not reach volcanic rock, arguments regarding the origin of atolls continued. The ideas of Murray and Daly have been referred to as the " antecedent platform theory", simply stated, reefs grew on pre-existing platforms. Daly (1932) analyzed atolls and concluded that the larger atolls had lagoons of uniform depth (70-90 m). He concluded that during the ice ages the cold waters' littled reef building organisms, exposing coastlines to erosion. The oceanic platforms were planed off by waves during periods of low sea level (when water was locked in ice caps).

After the ice ages, the seas warmed, coral thrived again, and corals grew to the sea surface, forming barrier reefs on the outer edges of the islands which had been partially truncated. This theory is referred to as the glacial-control hypothesis. Many important observations were made in Samoa early in the 1800s in order to evaluate these hypotheses explaining the nature and occurrence of Pacific coral reefs.

In 1918, Mayor observed wave cut benches around Tutuila at an elevation of 2-3 m above high tide. Daly (1924) observed similar wave cut benches and suggested that sea level was 2-4 m higher than present sea level. Observations were also recorded on the emergent wave-cut benches exposed on the eastern shore of Anau Island, Rose Atoll, Ofo, and Taa.

Daly (1924) states, "the prolonged denudation of Tutuila was naturally accompanied by the offshore deposition of much sediment." The sediment built broad shelves on the flanks of the seamounts. Daly estimated that the total area of shelf surrounding Tutuila is 330 square kilometers, within the 100-fathom (183 m) line. The shelf area is twice that of the island. These observations lend credence to the antecedent platform theory. Davis (1921) examined U. S. Hydrographic maps of Tutuila, and stated, "the shallower parts of the bank are interpreted as submerged fringing and barrier reefs, which are supposed to rest on a wave-cut platform now lying between 60 and 70 fathoms (109-128 m) below sea level by reason of island subsidence."

Chamberlin (1924) attempted to examine the coral reefs of Tutuila in terms of Daly's (1910, 1915) glacial control theory. Chamberlin states, "as far back as 1868, Alfred Tyler suggested that the upper 600 feet (183 m) of coral deposits in the Pacific Ocean might be explained as well by oscillation of sea level due to the ice cap of the glacial period as by the accepted hypothesis of sea-bottom subsidence."

Penck (1894), von der Decken (1897), and Daly (1913) estimated the lowering of sea level by withdrawal of water into Pleistocene ice-caps, between 150 and 55 m below present sea level.

Chamberlin (1924) examined the maps constructed by Mayor (1920). These maps indicate that submerged barrier and fringing reefs are present and are well highlighted by the 32-fathom (58 m) or 46-fathom (73 m) contours. Chamberlin also provided additional evidence of planation of Tutuila by point out the presence of eroded extrusive and intrusive bodies (e.g., cokcook chimney bodies) situated offshore Tutuila. He concludes the slopes of Tutuila extended at least halfway and likely much further, toward the margin of the existing platform. Chamberlin concluded the broad shelf was partly the result of erosion of the land surface and the buildup of detritus offshore and "parry from the work of the sea." He indicated that the extent of reef growth on the platform was uncertain. During the formation of the reefs, "the sea must have been creeping higher and higher upon Tutuila, as indicated by the vertical thickness of coral. Further subsidence followed the building of the reefs, for they are now deeply submerged." Chamberlin believed that the reef growth on a wave-cut platform rather than on the slopes of a sinking island represented a significant departure from the Darwin-Daly coral reef hypotheses. Davies (1921) however argues very convincingly that this idea did not represent a significant departure from Darwin's writings.

Daly (1924) raised a question about the absence of protecting reefs around Tutuila. Daly stated, "that the island was long devoid of protecting reefs, in spite of the existence of a shelf, is shown by the great height of the sea cliffs, cut before the 6 m shift of ocean level. . . . This reefless condition of the island may thus conceivably have been continued from the last glacial stage. But, the factor leading to the special prolongation of the reefless condition is not easy to discover." Daly (1924) concludes that "subidence, probably differential, [is required] in order to explain the drowned barrier reef around Tutuila."

Mayor (1924) reported on studies of the coral reefs of Samoan. His in situ investigations of sediment accumulation, dissolution, and so forth, are very insightful. He placed 3 lb (2.2 kg) fragments of tagged reef coral in the lagoon landward of the barrier reef. He removed nine months later and retrieved the stones. He found an average of 115 g weight had been lost. He estimated it would require only 14.5 years to "wholly disintegrate" rocks of this size. Mayor

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Studies of climate predict a rise of sea level. The nature and magnitude of such a rise is hotly debated. Global change and its effect on the Pacific islands has also been a topic of wide attention. Islands throughout the Pacific will be affected by even a small rise in sea level. Nunn (1988) has examined the possible arrays of inundation for selected parts of the Cook Islands, Fiji, Kiribati, Tonga, and Western Samoa. For Western Samoa, only the area around the capital city of Apia was examined. Nunn reports that most of the coastal mangrove coastal plains would be inundated by high rise. If the rise reached 1.5 m, most of the commercial center of Apia, the government building on the Maluina Point, and many of the hotels would not be exposed to the sea. A rise to 3.5 m would double the land area impacted and would affect most of the commercial and residential area of Apia.

General Unresolved Questions
About the Geology of Savaii
Most geological studies of Pacific islands have been concentrated on the islands of Hawaii. Thus the geological observations on Hawaii are generally used as examples of island volcanism to which all other island groups are compared. Relative to the Hawaiian group, the Savaii group appears anomalous. First, the islands grow larger from east to west, rather than west to east as in Hawaii. Second, active volcanism is recorded on both the eastern and western ends of the chain. In Hawaii, the active volcanism is found only on the eastern end. Third, the southeasternmost island in the Savaii chain is an atol rather than an active volcano. And finally, the tholeiitic rocks so abundant in Hawaii are nearly absent in Savaii. Alkaline rocks and transitional rocks are dominant in Savaii. These rocks constitute a veneer in the Hawaiian islands, but in Savaii appear to form nearly the entire mass of the volcanoes.

If Savaii is the proper corollary, then we should be able to use the age relations observed on Tutuila and Upolu to estimate the age of Savaii, providing the volcanic propagation rates are similar to those in Hawaii. Figure 33 illustrates the available radiometric dates for the Samoa chain. The extrapologation of age from the illustration suggests that the age for Savaii should be approximately 4 Ma. The palaeomagnetic data suggest ages from 1 to 3 Ma. The absence of older rocks on Savaii is a major concerne of scientists working on the Samoa islands. The majority of the landforms on Savaii are very young. Most geologists have assumed that the younger volcanism bury the much older shield-building volcanoes. Thus, a deeper isotopic core should be present and be simply capped by a thick sequence of eroded and weathered debris which is, in turn, covered by the Recent post-eruption basalts. If this is the case, this structure has important implications relative to
ground-water supplies. In order to examine the possibility, dredging is needed on the lower submarine slope of Savaii in order to obtain samples of the deeper shield-building tuffs forming the lower slopes of the seamount. Recently, a side-scan sonar survey was conducted on the southern flank of Savaii. The side-scan image shows the slopes are relatively free of volcanic cones. This lack of obvious volcanism, is suggestive that Savaii is indeed an old volcano with a thick cap of recent volcanism.

Tectonic setting

Studies of the bathymetric trends of the linear seamounts and island chains in the Pacific (e.g., Clague and Jarrard, 1973; Jarrard and Clague, 1977; Epp, 1979) have provided a great deal of information regarding the tectonic history of the Pacific plate. Linear seamount chains in the Pacific are numerous and varied. The Hawaiian, Emperor, and Lise Islands seamount chains are the best studied. West of these three seamount and island chains, however, the bathymetry becomes extremely complex, and the trends are so numerous that even the linear bathymetric trends become less apparent. Analyses of the bathymetric trends show that most of the Pacific seamount and island chains lie on parallel, small rises above Pacific plate hot spot positions. The Hawaiian Islands, and Emperor Seamounts have been associated with a melting anomaly (e.g., Morgan, 1972; Shaw and Jackson, 1979) referred to as a hot spot. Very limited radiometric, petrographic or paleomagnetic results are available from the western and southern Pacific seamount chains, particularly those that are old and submerged. Due to the lack of dating of the western Pacific seamount chains it is difficult to determine if these chains display simple single age progression patterns like the Hawaiian-Emperor chain, or if they were necessarily produced by passage of the Pacific plate over relatively fixed melting anomalies, or hotspots, in the mantle.

The Lise Islands chain, for example, has proven to be a composite of two or more major volcanic episodes (Jarrard and Clague, 1977; Jackson, 1976; Salto and Ozima, 1977; Jackson and Schlanger, 1976; Schlanger et al., 1984; Keating, this volume). Clague and Jarrard (1973) and subsequent workers have proposed that the Samoan seamounts are a hot spot trace. Hawkins and Natland (1975) and Natland (1980) suggest that plate deformation associated with subduction in the nearby Tonga Trench has influenced, perhaps even caused, Samoan volcanism. It has been suggested that the deformation has determined the location and orientation of Samoan shield volcanoes, and contributes to the unusual volume of post-eruption volcanic activity at the western end of the chain. This subduction-related deformation has determined the orientation of the post-eruption volcanic rift zone, and has deformed the sea floor around the Samoan islands.

The results of new studies provide basic observations that constrain the origin, age, and evolution of the Samoan Islands and Melanesian borderlands (Duncan, 1985; Duncan et al., 1985; Natland and Turner, 1985; Stinton et al., 1985; Keating, 1985). These authors suggest that the results of the individual studies are consistent with a hotspot origin for the Samoan Islands. In examining the data collectively, spatially of data becomes an important concern. At the present time, the paleomagnetic, radiometric, and geochronological data are very limited. The paleomagnetic data, for example, can be correlated with a hot spot model for the origin of the Samoan Islands. But at the same time, the available data can also be used to support a model for progressive volcanism toward Savaii, which is quite consistent with a hot spot model. Likewise, the existing radiometric dates on the islands are limited; they allow a positive correlation with a hot spot model in only two islands and two seamounts west of the Samoan chain. Thus, although the data are "broadly consistent with a hot spot model of origin for the volcanism" as stated by McDougall (personal communications, 1984), it is important that variations of the hot spot model of origin be examined in order to explain the anomalous patterns of volcanism observed in the Samoan Islands.

Duncan (1985) shows that recent (0.8 Ma) volcanic activity has occurred on Wallis Island (roughly 30 km west of Savaii; Fig. 36). On the basis of the present geologic knowledge of the Samoan islands, it is likely that the latest volcanism is contemporaneous on Wallis, Savaii, and the Manua islands. Could these three islands be related? They form a linear trend that cuts across the main trend of the Samoan group. Assigning a deformational history to this recent activity, as suggested by Natland, resolves many of the anomalous features of the volcanic propagation in the Samoan chain. Continued studies of the age, geochemistry, and magnetic history associated with mapping of these islands and seamounts are the key to our knowledge of the evolution of this unusual chain of islands and seamounts.

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