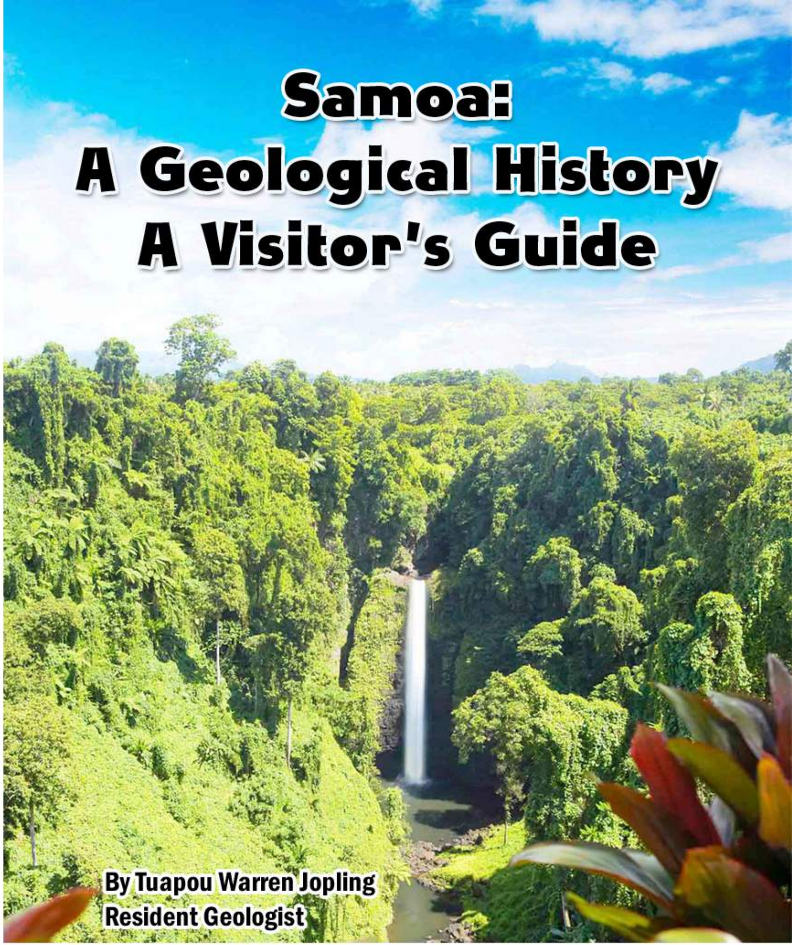
Samoa:
A Geological History
A Visitor's Guide



By Tuapou Warren Jopling
Resident Geologist

SAMOA
The Treasured Islands of the South Pacific

FAAVAE I LE ATUA SAMOA

NEW ZEALAND
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Brief Background

Notes on the earth's composition, plate tectonics and palaeomagnetism are separated from the text as many readers would already be familiar with these processes.

This guide was written in collaboration with the Samoa Tourism Authority. It outlines how the Samoan Archipelago formed, why one island suffers massive periodic eruptions and why volcanism is predicted well into the future. Geology is an aspect of tourism seldom presented to visitors, most of whom return home with wonderful tales of people, culture and beaches but quite unaware they just left a unique chain of volcanic islands – active at each end and the site of one of the world's largest lava eruptions of historic time.

This, then, is primarily for visitors interested in natural history. It is neither a scientific treatise nor a travel guide to Samoa's many scenic highlights but a narrative explaining Samoa's two stages of volcanism, why it took most of the 20th century to establish the archipelago's hot-spot origin and why Upolu and Savaii are so different in landscape and population.

Some understanding of the earth's composition, plate tectonics, palaeomagnetism and hot-spots is helpful in following this story. Hot-spots are described in the text, the others briefly outlined in an appendix.

About the Author

Warren Jopling is a retired Australian Geologist who resides on the island of Savai'i and runs natural history tours for visitors and student groups from American, Australian and New Zealand schools and universities. He frequently works with the Samoa Tourism Authority in promoting Samoa overseas in television documentaries and newspaper media. He can be contacted directly by cell phone (685 750 6448) or through the STA website (www.samoa.travel)

THE SAMOAN ARCHIPELAGO.

The Samoan Archipelago is a chain of nine inhabited islands, several small uninhabited islands and, at its easternmost extremity, a very large submarine volcano. (fig.1)

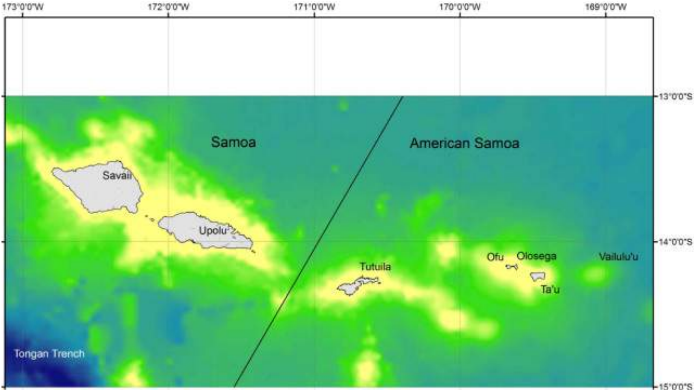


Figure 1: The Samoan Archipelago

The 400km long archipelago trends west-northwesterly through the territorial waters of American and Independent Samoa and is the easternmost and youngest segment of a long volcanic trail known from argon rock dating to extend 1300km WNW of Samoa. The seamounts on which the coral atolls of Tuvalu, Kiribati and the Marshall Islands are located may be extensions of this trail (fig 2).

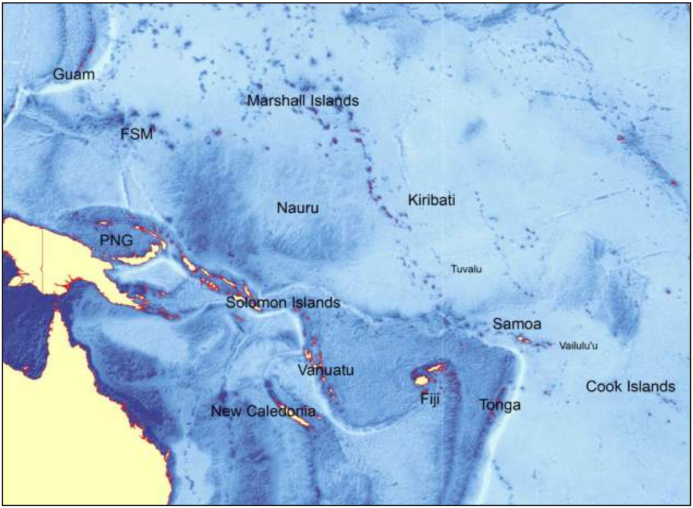


Figure 2: The Samoan Volcanic Trail

Discussion focuses on Upolu and Savaii of Independent Samoa, on the Mt Vailuluu submarine volcano of American Samoa and, from a regional perspective, on the Hawaiian Archipelago 4000km to the north of Samoa and the Tonga Trench 200km to the south.

Particular emphasis is on Savaii, Samoa's oldest, largest and most westerly island and the only one to have experienced massive eruptions during historic time. (Historic time does not refer to the arrival of Polynesians some 3000 years ago but to the first sighting of the islands by a Dutch navigator in 1722)

THE PACIFIC PLATE, HOT – SPOTS AND HAWAII.

The Pacific Plate is born along the East Pacific Rise, the divergent plate boundary where convecting cells of upper mantle basalt surface and spread apart – the Nazca, Cocos and Juan del Fuca Plates moving eastwards and the enormous Pacific Plate moving to the northwest (fig. 3)

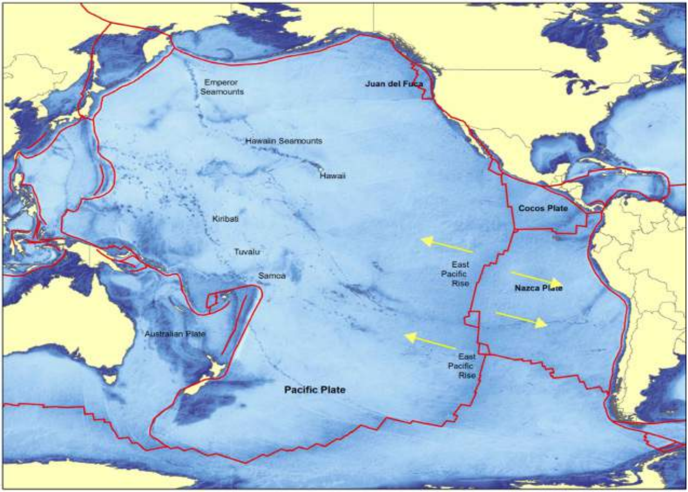


Figure 3: Pacific Ocean Plates

The plate ages progressively away from the East Pacific Rise and in the areas encompassing both Samoa and Hawaii is approximately 100 million years old. Direction and rate of movement vary slightly across the plate with the Samoan Islands moving 7.1 cm yearly to the west-northwest – 71km per million years.

The crust is 5km or less in thickness, rigid and heavily fractured allowing mantle material to rise and build ridges over many parts of the ocean floor. These, unlike hot-spot trails, are not necessarily aligned with plate movement.

A hot-spot is described as a stationary area in the earth's mantle where heat escapes as a rising plume of molten or semi – molten magma. This melts through the overlying plate to form a seamount or, when magma supply is plentiful, a volcanic island. These features are slowly carried away and new ones form to create a volcanic trail of islands, seamounts and deep-water passages from periods of reduced magma supply.

The Hawaiian trail is the longest and best documented of the seven hot-spot trails scattered over the Pacific Plate. Hawaii, the largest and most easterly island of the Hawaiian Archipelago rises 9.5km from the ocean floor, the topmost reaches of this enormous volcanic shield being snow – capped. Hawaii has built up over the Hawaiian hot-spot and is continuously eruptive – mostly quietly but with spasms of spectacular activity about every three years.

Plate movement can be traced northwestwards from Hawaii through the high volcanic islands of Maui, Molokai, Oahu and Kauai, then by the Hawaiian and Emperor Seamounts over a distance of 7300km, pointing to hot-spot activity of 70 million years or more.

THE SAMOAN ENIGMA AND SOME EARLY VOLCANIC HISTORY

Now to the Samoan Archipelago, parallel to the Hawaiian chain, composed of similar basaltic rocktypes but with the large, periodically eruptive island of Savaii at the western end of the archipelago. There was no explanation to this enigma at the time of Savaii's 1905 – 1911 eruption. Alfred Wegener's theory of 'Continental Drift' was about to astound the world, oceans had not been systematically mapped and the science of volcanology was in its infancy. Eruptions happened but nobody knew why. Thirteen major eruptions were recorded around the Pacific's 'Ring of Fire' during the 19th century, two in the Dutch East Indies (Tambora, 1815 and Krakatau, 1883) together accounting for 96,000 lives.

There was considerable awareness of volcanic hazards by the turn of the 20th century, quickly heightened by three horrific eruptions in 1902 – Mont Pelee, Martinique, 28,000 + deaths; Soufriere, St Vincent 1600 + deaths and Santa Maria, Guatemala 7000 + deaths. 1902 was also the year of Savaii's Mauga Mu eruption but this was short-lived, in a remote part of the island and caused no loss of life. It was not widely publicized.

Mauga Mu was a precursor to the Mt Matavanu eruption of 1905 – 1911, the largest eruption of the 20th century in extruded lava but not violently explosive and causing no deaths.

Eruptions continued throughout the century but with little understanding until the 1960s when the basics of the Plate Tectonics were established. Systematic ocean – floor mapping revealed plate boundaries – the high mid-ocean ridges where plates are born and the deep ocean trenches where they subduct and are re-melted into the mantle.

Figures 1, 2 and 3 show Samoa's proximity to the Tonga Trench. The Pacific Plate is slowly carrying Samoa towards Asia but, 200km to the south, it subducts under the lighter rocks of the Tonga Block which forms the northeast corner of the Australian Plate. The area north of the trench encompassing Savaii and Upolu is heavily deformed by the plate's westerly movement against the rapid (190 km per million year) easterly swing of the Tonga Trench (Fig 4).

Savaii's historic eruptions and those of the preceding 390,000 years that have built up thick stacks of volcanic rocks over Savaii and all but the northeastern quarter of Upolu are attributed to magma surfacing along fracture zones and faults from a shallow upper mantle magma pool. The major fracture zones are caused by shearing aligned with plate movement, the most obvious fracture extending the entire length of Upolu into Savaii – a distance of over 200km. This has been active magma conduit for the past 390,000 years but the faulting responsible for Savaii's historic eruptions is no older than 20,000 years. This is discussed later.

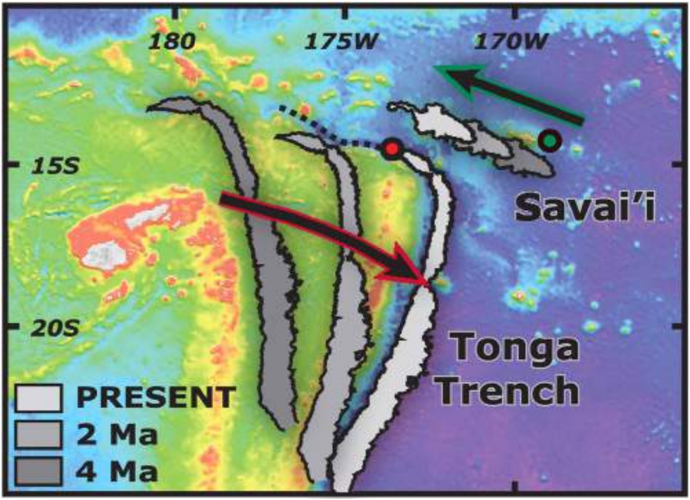


Figure 4: Tonga Trench Rollback

Eruptions are infrequent, memories short and the events of 1905 – 1911 and earlier eruptions largely forgotten. But all Samoans are aware of earthquakes, many still mourning their losses from the deadly 2009 tsunami.

Occasional earthquakes and daily tremors (recorded but too small to be felt) are manifestations of Samoa's tectonic instability. Most are generated by slippage in the Tonga Trench subduction zone but the tsunami was from a triple event lasting two minutes.

The Pacific Plate itself ruptured triggering two earthquakes at the plate boundary (Fig 5). A rupture (probably aligned with plate movement) and sudden subsidence to the north directed the main tsunami waves towards Upolu and Tutuila but caused only minor damage in Savaii.

Intra-plate earthquakes are less frequent than quakes at plate boundaries but the elongate ruptures through Upolu and Savaii indicate intra-plate deformation of massive scale.

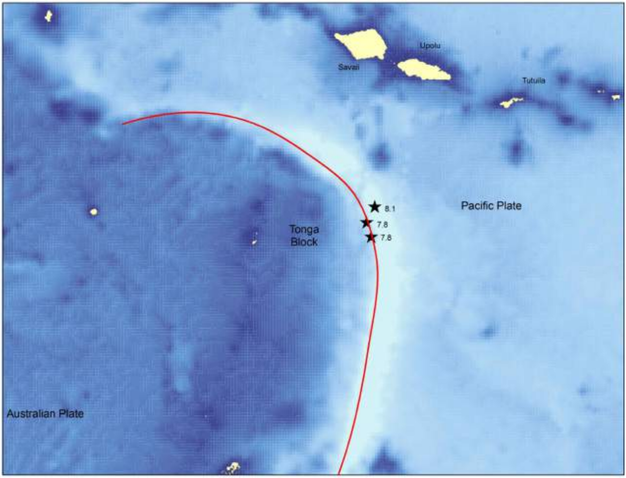


Figure 5: Tsunami Earthquakes

Proximity to the Tonga Trench explained eruptions but the big question remained unanswered. Was Samoa part of a hot-spot trail?. The small volcanic islands of American Samoa bore little resemblance to Hawaii and a short-lived submarine eruption between Olosega and Ta’u in 1866 was not consistent with continuous hot-spot activity.

The hot-spot uncertainty has been resolved during the past 30 years, firstly by detailed bathymetric mapping around American Samoa and more recently by dating Savaii’s oldest rocks.

Ocean floor mapping located a submarine volcano - Mt Vailuluu - 45km east of Ta'u, American Samoa's most easterly volcanic island. It rises 4.5km from the ocean floor, has a crater 2km in diameter, 400m deep and is continuously venting mineral – charged hot water. Ten years ago a cone was growing inside the crater at 20cm daily but has since subsided. Mt Vailuluu is over the Samoan hot-spot but still 590m below sea level. It is expected to grow and possibly emerge to add another island to the Samoan chain before moving westwards off the hot-spot.

Argon dating of unweathered basalt samples from the base of one's Savaii's deeply incised valleys showed a five million year age. Other samples collected by dredging the low submarine flanks of the island showed comparable ages. This dating with the known rate of plate movement firmly establishes a linear – age progression. Savaii , now 400km west -northwest of Mt Vailuluu, formed over the hot-spot 5 million years ago.

In summary, the original hot-spot (shield building) volcanics of Savaii and Upolu were deeply eroded during a long period of sub-aerial exposure before the second phase of volcanism started some 390,000 years ago. This blanketed all of Savaii and most of Upolu but subsequent stream erosion in Savaii re – exposed a small area of the shield building rocks.

ROCK FORMATIONS

Samoa's volcanic rock formations are named after the localities or villages where they outcrop and in order of age are Fagaloa, Salani, Mulifanua, Lefaga, Puapua and Aopo, Fagaloa being a bay of northeastern Upolu, Salani, Mulifanua and Lefaga coastal villages of Upolu, Puapua a village of Savaii's east coast and Aopo an inland Savaiian village.

These names are taken from the standard reference to Samoan geology "The Geology and Hydrology of Western Samoa," New Zealand Geological Survey, bulletin 63, 1959. The authors, D. Kear and B.L.Wood, prepared the report from field trips and air photos from mid-August to late October, 1956. It was a monumental work but, as acknowledged by the authors, subject to considerable revision. The original mapping must have being difficult-restricted time, a heavy vegetative covering over most outcrops and little variation in the lithology of the basaltic rock types that cover both islands. Age dating might have established a time relationship between the various rock units but this is reliable only with unweathered samples so was not done.

The formation boundaries on the geological map (fig.6) were selected mainly on the degree of surface weathering – old outcrops being heavily weathered and with deep soils, young outcrops being bouldery at surface and with thin soils. Topography was also considered. Permanently flowing streams in deeply incised valleys are found only in Fagaloa (and possibly early Salani) areas where clay has sealed surface porosity. Mulifanua to Aopo areas have shallow, mostly dry stream beds (alias) which flow briefly with torrential rains, rainwater quickly becoming groundwater. This is discussed later under hydrology.

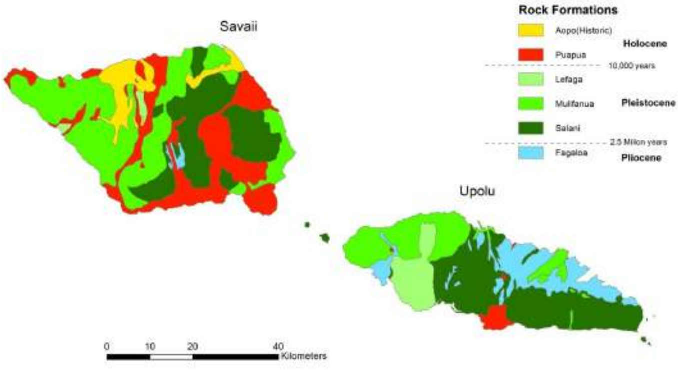


Figure 6: Samoan Rock Formations

Rock samples from many areas of both islands were tested for magnectic properties during the mid-1980s. (Palaeomagnetsium or fossil magnetism is discussed in the appendix). Rocks from Upolu's southeastern corner, originally mapped as Salani formation, show reverse polarity indicating 'hot-spot' origin, i.e. Fagaloa formation. Conversely, samples from Savaii's northeastern area mapped as Fagaloa showed normal polarity so are probably of Salani age.

Surface weathering may be helpful in determining comparative ages of rock outcrops but it is subject to climatic factors and the physical nature of the rocks – a thick, dense lava flow will weather more slowly than fragmented volcanic ejecta. The most reliable way to establish a stratigraphic sequence is to date rock outcrops from each island. So far this has not been done.

Fagaloa volcanics (fig 7) outcrop over northeastern Upolu and a small area over the island's southwest. Savai'i is covered with post-Fagaloa volcanics, the only proven Fagaloa outcrop being downstream from the high Sinaloa Waterfall. Rock samples from this outcrop have been dated at five million years.

Other outcrops could occur in adjacent canyons of the island’s southern flank but the area is difficult to access and has not been rock sampled.   The formation consists mostly of basalt flows from a few centimeters to 30m in thickness with interbeds of scoria, cinders and ash. Olivine phenocrysts are common in the flow lavas. Many dykes (vertical to near-vertical walls of intrusive basalt) cut through the Fagaloa rock stack but are absent in the higher Salani to Aopo rock units.

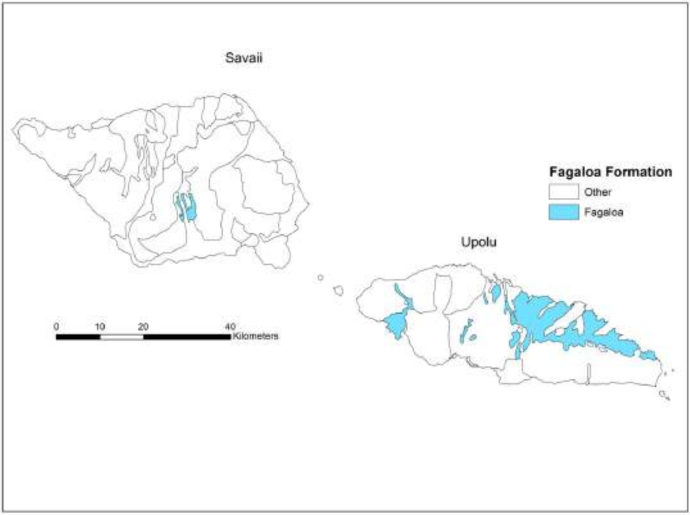


Figure 7: Fagaloa Formation

Upolu’s Fagaloa outcrops, now exposed to some four million years of erosion, present a spectacularly rugged landscape of steeply weathered slopes, high ridges, mountain peaks and deeply cut valleys with waterfalls. Coastal topography is equally impressive where steep cliffs descend into near-shore deep water thereby preventing growth of offshore coral. Patches of fringing reef grow along the shoreline but do not enclose lagoon.

Tourists wishing to see some of Upolu’s most beautiful scenery should travel the coastal road eastward from Apia, turn at Lufilufi into the Sauniatu valley, continue along the coastal road to Falefa, cross the island by the Le Mafa pass to Lotofaga on the south coast and continue eastwards to Upolu’s easternmost point where, on a clear day, the top of American Samoa’s Rainmaker Mountain is visible.

Salani volcanics unconformably overlie the deeply eroded Fagaloa surface. Activity started 390,000 years ago, probably in Savaii before Upolu due to the eastward migration (rollback) of the Tonga Trench. All of Savaii and the western half of Upolu were covered in thick lava flows, scoria and ash beds but the mapped Salani units of each island might differ in age.

Mulifanua lavas, scoria and ash beds cover the western sectors of both islands and probably overlie a weathered Salani surface. They form gentle slopes extending beyond today’s shoreline so were laid down during the last Ice Age when sea was 120m lower than to-day. Wide lagoons are distinguishing features of Mulifanua coastlines. Rock dating is needed to establish the Salani – Mulifanua relationship between Savaii and Upolu, also to determine any significant time lapse between these rock units. The Mulifanua – Lefaga relationship is also unclear, Lefaga volcanics being mapped in Upolu but not in Savaii.

Before discussing Puapua and Aopo volcanism a note on changing sea level is needed to explain why Savaii's post-glacial geology differs from that of Upolu. For most of the past 2.5million years (i.e. the latter half of Samoa's geologic history) much of the Northern Hemisphere was under a thick ice pack. The Ice-Age (Pleistocene) was interspersed with 14 or 15 interglacial periods, the last one starting about 21,000 years ago. Sea rose 120m, slowly during the first six thousand years of the meltdown, rapidly (approximately 1.4cm yearly) from 15,000 to 7000 years ago then slowly until to-day. Rise over the past 7000 years has been approximately 4m (fig 8).

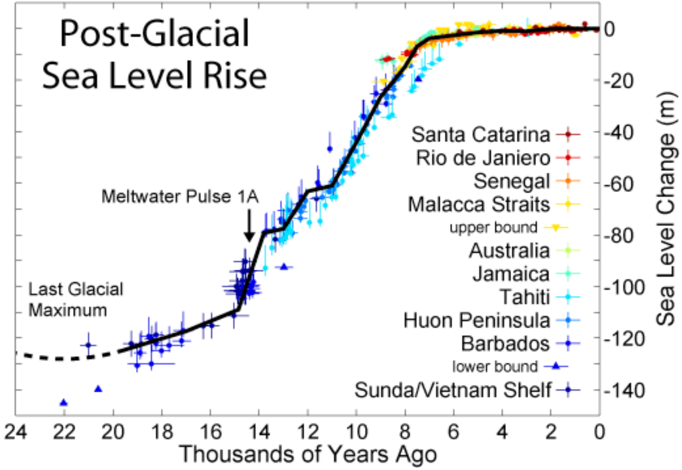


Figure 8: Sea Level Rise

Rising sea has profoundly affected Samoa’s post-glacial geology. Firstly, old coral reef would have been drowned out by the rapidly rising sea of the post-glacial meltdown. New coral growth could have started about 7000 years ago and grown apace with rising sea. The reefs that surround 65% of Upolu’s shoreline and 25% of Savaii’s are therefore young. Secondly, both islands have reacted to hydroisostatic rebound, meaning the islands have risen because of rising sea. This defies logic but is easily explained. The weight of the 120m sea rise has pressed the thin Pacific Plate surrounding the islands into a shallow, underlying magma chamber. Magma has flowed and accumulated below the islands causing uplift. Emerged shorelines of two to three metres can be traced around both islands, particularly along Savaii’s south coast where many wave-cut caves have been cut into basalt cliffs and are now well above wave level. Hydroisostatic rebound was not restricted to Samoa. It was a worldwide phenomenon affecting every island located on a thin plate of oceanic basalt. Average emergence was 1.5 metres. Savaii's 2-3 metre rise might be attributed to its position over a shallow magma pool.

The meltdown was coincident with (and possibly the cause of) a period of intense volcanism in Savaii but not in Upolu. Puapua volcanics cover 20%of Savaii but only 30sq.km of Upolu. (fig 9). Savaii’s central plateau is studded with Puapua ash, cinder and lava cones. Samoa’s four largest sub-aerial cones (Tafua-upolu, Mafane, Tafua-savaii and Toi’avea) are classified as Puapua- large for Samoa but miniscule when compared to the world’s strato-volcanoes.

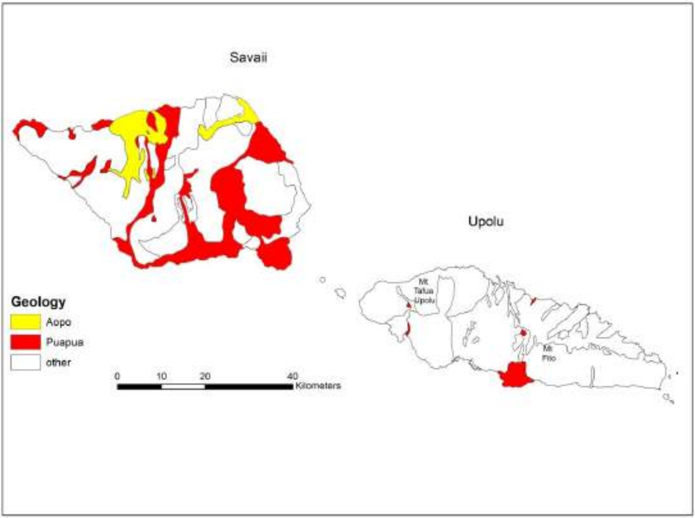


Figure 9: Aopo and Puapua Outcrops

The 10,000 years Pleistocene – Holocene (Recent) time division is also taken as the division between Puapua and Mulifanua activity. Timewise this is in the middle of both the glacial meltdown and a period of a frequent eruptions. Rock dating is needed to differentiate between late-Mulifanua and early Puapua outcrops or, preferably, a new formation name should be assigned to all the rocks of this period of intense volcanism.

SAVAII'S HISTORIC ERUPTIONS – AOPO FORMATION.

Early Polynesians would have witnessed many eruptions since arriving in Savaii 3000 years ago and volcanism might have prompted their later migration to eastern Polynesia. But early oral history has been lost so the only reliable accounts of the first two historic eruptions are those of the French navigator Anton Bougainville who sailed by Savaii's north coast in 1768 and by the German colonists who occupied Samoa at the time of be the small 1902 eruption. Volcanologists consider the 1760s MaugaAfi (mountain of fire) eruption to be one of the largest in extruded magma of the past several thousand years.

The 1760s outbreak was from two cones spaced 3km apart on Savaii's high central plateau. Lava from these (MaugaAfi) coalesced and flowed down the island's steep northern flank forming a wide lava fan over the coastal plain. There is no record of the start or end of this eruption but it was very big, probably long lasting and covered over 100sqkm to an unknown thickness. An old legend tells of 100 buried villages – probably an exaggeration but certainly indicating a high pre-eruptive population. Samoans, then as now, traditionally lived in villages along lagoons. The basalt cliff along the still smooth coastline probably built up over a coral reef, events that were replicated 150 years later during the Matavanu eruption.

The short-lived eruption of 1902 was also on the high central plateau 4km east of Mauga Afi. The area was shielded from coastal view by the island's gentle curvature so it was not known if existing cones had erupted or if new ones had formed. Subsequent investigation showed two closely spaced clusters of new spatter cones, thereby adding eight small cones to the hundreds already existing.

Mauga Mu was the beginning of a cycle of activity which culminated with the massive 1905 – 1911 eruption of Mount Matavanu, Samoa's first eruption to be well documented.

Figure 10 of central Savaii shows the village of Aopo and the eruptive centers of the 1760s (Mauga Afi) and 1902 (Mauga Mu) outbreaks. It also shows cone distribution over part of the same area.

Figure 10: Kear & Wood, Savaii's Central Plateau

THE 1905 – 11 MATAVANU ERUPTION

Matavanu's birth on August 3 1905 was impressive. High lava fountains blew from a cattle grazing area, quickly built a spatter cone and by early- September great surges of incandescent lava were flowing down a dry river valley towards the Saleaula coastal plain.

By September, 1906, five villages had been overwhelmed, the lagoon along the shoreline had been filled and 76sq.km of farmland buried under basalt. Activity continued until late 1911, but at a much reduced rate with molten lava reaching the ocean via lava tunnels. This fragmented into black sand on dropping into water and was dispersed by currents and waves. (Sufficient sand was washed back over 5m high cliffs during the 1990 Cyclone Ofa to start a home industry – black sand building blocks).

The Mauga Mu and Matavanu eruptions were vastly different to the catastrophic 1902 eruptions in the Caribbean and Guatemala. Both were mildly explosive but caused no deaths; and both were from new cones rather than from existing cones indicating monogenetic volcanism.

ERUPTIONS – THE DANGER FACTOR.

All magmas consist primarily of oxygen, silicon, aluminium, iron, magnesium and calcium in different proportions but it is silicon content which largely determines if an eruption will be mild or explosive. The basalts of the Pacific Plate and its intra-plate islands (Hawaii, Samoa) have low silicon content, all of which is combined with the metallic elements as minerals called silicates. There is no free quartz (silicon dioxide).

These lavas have temperatures of about 1200ºC on emission and consequently are sufficiently fluid to allow dissolved gasses to come out of solution and escape at the volcano's vent. Gas pressure doesn't build up in the volcano causing it to explode. (Steam is a gas and the main driving force in all eruptions, either flowing or blowing).

Magmas with high silicon content can be very dangerous. Volcanoes over subduction zones (where a plate of oceanic basalt subducts under and melts an overlying continental plate of highly silicious rocktypes) can explode violently. Temperature of a silicious magma on emission can range from 800ºC to 1000ºC. This cooler magma can be too viscous to allow gasses to escape. Gas pressure will mount until the volcano explodes releasing a searing, rapidly expanding cloud of steam and toxic gasses charged with ash.

Some readers would know about the 1902 eruption of Mont Pelee, Martinique, which completely destroyed the original capital St Pierre killing 28,000 residents; and many readers would remember the 1980 eruption of Mt St Helens, Washington State, which killed 57 old-timers who refused to evacuate. These are Pelean eruptions where a pyroelastic flow (or nuee ardente) blasts laterally and, together with Plinian eruptions where the blast is vertical, are the most dangerous. (Pliny the Elder died in the AD 79 eruption of Vesuvius). The Samoan eruptions are at the bottom of the danger list and are called Hawaiian – type or moderate eruptions.

VOLCANIC CONES.

500 or more cones dot Samoa's landscape and many others would have been buried under later eruptions. The number is impressive but not the cones themselves, very few rising more than 150m above ground level. The size of a cone does not necessarily equate with the volume of its eruption, as shown by Savaii's enormous outbreaks of the 1760s and 1905-11. Low profile lava cones are outnumbered by steeper ash and cinder cones but their combined output of lava and volcanic ejecta (tephra) has built thick stacks of volcanic rocks over both islands in the geologically short period of 390,000 years.

Fagaloa cones are either buried under younger volcanics or too weathered to be recognizable. Visible cones range in age from Salani to historic with most Holocene cones (those of the past 10,000 years) concentrated in Savaii.

Upolu 's 47 cones are aligned along the island's ESE-WNW trending central spine. The trend continues to Manono Island (originally Upolu's westerly tip before being separated by rising sea), to the Apolima tuff cone in the deep part of the Apolima Strait and to the Tafua-savaii volcano on Savaii's southernmost tip. This alignment parallels Pacific Plate movement and is the result of an elongate fissure in the plate caused by shearing.

Distribution of Savaii's 450 + cones is more complex but, as in Upolu, the dominant trend is aligned with plate movement. Other short chains of closely spaced cones line the surface trace of a large normal fault and other cones seem to be randomly distributed.

Faulting and shearing of the plate have provided convenient conduits for rising magma and, from the evidence of the 1902 and 1905-11 eruptions which built new cones, it is assumed that magma of future eruptions will also build new cones rather than follow earlier conduits plugged with basalt i.e. monogenetic volcanism.

Figure 11 and 12 show cone distribution of Upolu and Savaii from the Geology and Hydrology of Western Samoa.

Figure 11: Upolu Cone Distribution and Faulting

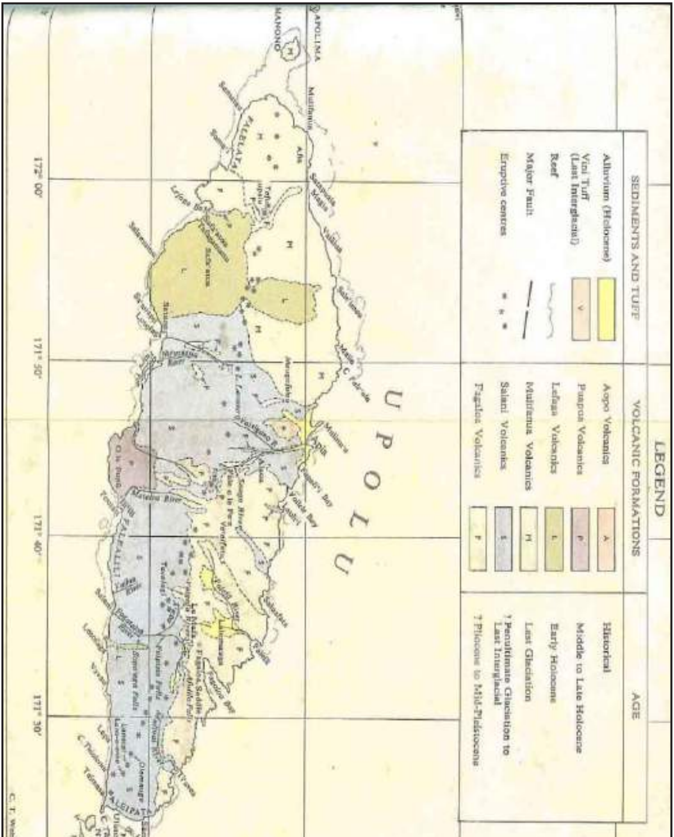
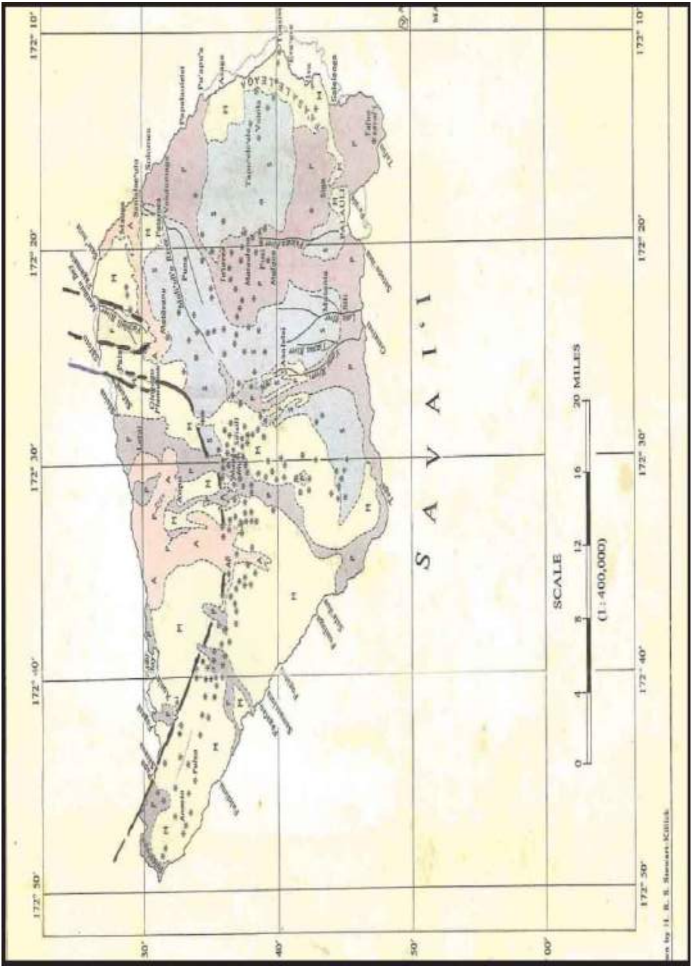


Figure 12: Savaii Cone Distribution and Faulting



STRUCTURES

Samoa's most prominent structural features, already mentioned, are the broad bands of volcanoes overlying fracture zones caused by shearing. They are well defined on air photos but alignments are mostly not recognizable from the ground. Upolu's topography is too broken and the cones too irregularly positioned to form any clear picture of the dominant ESE –WNW trend; and the majority of Savaii's cones are on the high central plateau hidden from coastal view.

Passengers approaching Savaii by ferry will see the 7 easternmost cones of the Tuasivi Ridge which is parallel to but 14 – 15km north of the main cone alignment extending through Upolu, Manono, Apolima, Tafua and the western sector of Savaii – i.e. broad belts of volcanoes aligned with plate movement.

Late Pleistocene faulting (20,000 to 10,000 years ago) has provided magma conduits in Savaii. Savaii is cut by many small normal faults (i.e faults causing vertical displacement of rock strata) and an extensive fault system resulting in 20% of the entire island slumping northwards. Figure 12, adapted from the original 1956 field mapping, shows a long curved fault flanked on the east by two step faults. The broad curvature of the main fault indicates the collapse of a thick stack of poorly consolidated volcanic ejecta and flow lavas probably destabilized by rapidly changing sea level. The fault displaces Salani and Mulifanua beds and is partly covered by Puapua and Aopo flows. Consequently it is young, probably relating to rising sea of the last glacial meltdown. Cones of late-Mulifanua age and those of the 1760s and 1902 eruptions are on or close to the surface trace of this main fault. It has a vertical displacement of 150m south of Aopo and cuts the coastline at Safune in the east and Sataua in the west forming steep scarps into these villages. Visitors stop to photograph the magnificent coastal panoramas from the road above these villages without realizing the geological significance of these slopes.

Mt. Matavanu, Savaii’s last cone to form, has built up over the step fault east of the main fault. The 8km long access road from Safotu to Matavanu is along the downthrow of a very steep 30m high fault scarp to the base of the volcano where the scarp is buried under volcanic spatter. Here the road rapidly climbs the volcano’s north flank and the lush tropical vegetation is replaced by thin scrub.

Fault escarpments of 30m and 150m provide spectacular scenery but they are not major structural features. The landslide was immense, 42km wide at the coast and extending 13km inland but its confining faults are far too small to have intersected an underlying magma source. But Savaii is the pinnacle of an enormous edifice of hot-spot origin capped by younger volcanics. The edifice rises 6.8km from the ocean floor with sub-aerial Savaii accounting for only 3% of the total structure. The landslide and its confining faults are surface expressions of considerable disturbance in sub-marine levels of this edifice.

A 20km long vertical cliff of black basalt forms the shoreline of Savaii’s southwestern coast between Foailalo and Fagafau (Lovers Leap). It rises gently in height from 30m at Foailalo to 75m west of Fagafau and could be either a fault scarp or an erosional feature caused by waves undercutting heavily jointed Mulifanua basalt flows. Molten lava shrinks on consolidating leaving a pattern of vertical joints. When undercut by waves, blocks slough off along joint planes. Whatever the explanation, this section of Savaii is beautiful - picturesque little villages perched high on a cliff overlooking the ocean.

UPOLU AND SAVAII – THE DIFFERENCES

	UPOLU	SAVAII
Area sq. km	1100	1868
Population 2011 census	142,000	44,000
Percentage of total	77	23
Population per sq. km	129	24

The above figures are approximate and population would have risen since the 2011 census but the salient point is that Savaii, the larger island, has a lower population and much lower population density than Upolu. There are many reasons for this, some social (better work opportunities, tertiary education, health care, good shopping, cinemas, niteclubs etc), the other reasons physical. Some Savaiians moved to Upolu following the devastating category 5 cyclones of 1990 and 1991 but the main cause of Savaii's low population is geological.

Two factors need mention – firstly lagoons. (A lagoon is the body of seawater enclosed between the shoreline and an offshore coral reef.) Samoans mostly live in villages by lagoons. It is both pleasant and an important source of food.

A wide lagoon surrounds most of the western half of Upolu, the island's easterly tip and there are several pockets along the northeastern shore. Fringing reef (that growing in contact with the shoreline) occurs along most of Upolu's southeastern shoreline and in places has advanced sufficiently seawards to enclose a narrow belt of water.

Parts of the northeastern shoreline where Fagaloa cliffs dip steeply into deep water have no reef and there is no reef along the 12km long of Puapua outcrop of the south-central coast.

Approximately 65% of Upolu's coast has offshore reef, the remainder having fringing reef or no reef.

Five sections of Savaii have offshore reef but are widely separated by long stretches of iron-bound coastline – an old mariner's term for black basalt cliffs plunging vertically into the ocean. Lagoons account for only 27% of to-day's coastline. It is assumed that much of Savaii was once surrounded by lagoons but now filled or partially filled with Puapua and Aopo basalt. Figure 8 shows these outcrops to cover 30% of the island but concentrated in coastal areas. 50% of coastal Savaii is geologically very young.

The second factor has already been partly covered. Villagers lacking employment live by subsistence farming, successful only with adequate soils. Much of coastal Savaii is too young for sustainable agriculture. Trees will grow because their roots get into the joints between basalt blocks but ground crops requiring a depth of soil do poorly.

These are the reasons why Savaii's population is low – not only low but static. Despite a high birth rate of 4.7 children per adult pair there has been no increase in population over the past 22 years, the last three censi showing 45,000, 42,000, 44,000 people.

The factors that make Savaii unattractive to a Samoan farmer are exactly those that delight the tourist. Very few Pacific islands have such a combination of spectacularly rugged iron-bound coastline, beautiful coral sand beaches and pristine lagoons.

THE FUTURE

Savaii has been the centre of intense volcanic activity over the past 20,000 years with historic eruptions 150 years apart. Rising sea during the last glacial meltdown could have induced some or all of this activity but without age dating it is impossible to establish a pre-historic sequence of volcanic events. Basalt samples from all post-Fagaloa rock units of Upolu and Savaii need to be dated to determine how these units correlate and determine an eruptive pattern for predicting future outbreaks. The next one could be anywhere within the Samoan Archipelago but probably in Savaii and, if resembling the 1905 – 11 event, it will be massive, long-lasting but not highly explosive and consequently not life-threatening.

Despite the uncertainties of the near-future, the distant future is very predictable. The inexorable westerly journey of the Pacific Plate and the easterly roll-back of the Tonga Trench will continue with Samoa remaining vulnerable to eruptions, earthquakes and tsunamis for the next several million years.

HYDROLOGY.

Rainfall for both Upolu and Savaii is high, ranging from 4000 to 7000mm annually in high central areas to 2000 to 3000mm for coastal areas. Despite high rainfall, there are few permanently flowing streams except in eastern Upolu where clay of weathered Fagaloa and early-Salani outcrops has sealed surface porosity. Savaii has two small permanently flowing creeks also in Salani outcrop but the Lata River, Savaii's largest stream, occasionally dries during rainless periods. Mulifanua, Puapua and Aopo surfaces are too porous and permeable to hold water.

Torrential rain will cause the alias to flow but within hours they usually dry.

Savaii and the western half of Upolu consist of thick stacks of poorly consolidated volcanic ejecta and heavily jointed lava flows. Rainfall sinks into these formations then, as groundwater, percolates down to enter a fresh-water aquifer at sea level. This Ghyben – Herzberg Lens is explained thus; rocks that are porous and permeable to rainwater are also porous and permeable to seawater. Saltwater underlies the island, saturating pore space between rock particles and the joints and fractures of lava flows. The seawater has mineral content and cradles the lighter fresh-water. A Ghyben-Herzberg Lens is thick in the central part of the island, tapers towards the coastline and is underlain by a zone of mixing, then of seawater. The lens is being added to constantly by groundwater and is under pressure from below by seawater trying to regain sea level, resulting in fresh-water being discharged continuously around the shoreline as seepages and springs.

Most coastal villages of Savaii and western Upolu have walled-in springs, the water being fresh from low-tide to half-tide then brackish to high tide. Pool water is used for bathing and washing clothes but, without boiling, not for drinking. Savaii's domestic water supply is heavily dependent on inland wells where the Ghyben-Herzberg Lens is thick and uncontaminated by village sewage.

TAFAGAMANU SAND, SEA LEVEL AND LAGOONS.

Long flat strips of well-compacted coral sand outcrop along all sections of coast protected by offshore coral reef and lagoon. Approximately two-thirds of Upolu and one quarter of Savaii are fringed with this Tafagamanu Sand and the majority of Samoa's coastal villages are built on it. The strips vary from narrow to over a kilometre in width and, when wide, are sometimes backed by wetlands.

Tafagamanu Sand was probably lagoonal fill of mid-Holocene age, raised by hydroisostatic rebound of the last glacial metdown. Sea rose rapidly from 15,000 to 7,000 years ago then slowly until to-day (fig.7). The fact that Tafagamanu Sand post-dates the rapid rise is evidence for rebound continuing well into the Holocene and, possibly still active to-day.

Early coral reef would have been drowned by rapidly rising sea of the metdown with new growth starting within the past 7,000 years, firstly as fringing reef along a shoreline then advancing seawards towards incoming plankton-bearing waves. The reef would rise with rising sea to form an offshore reef enclosing a lagoon.

Sea level has risen approximately 4m during the past 7000 years (fig 7). Lagoons should be deep near the shore then shelve towards the reef but there is little ground evidence to support this, most lagoons being quite shallow. The writer cannot comment objectively on Upolu but knows Savaii very well. The lagoons between Saleaula and Sasina (north coast) and between Salailua and Satuiatua (south coast) are drained at low tide exposing long sections of lagoon flat. Tidal range is between 0.9m and 1.8m so lagoon depth never exceeds 1.8m (except during cyclone surge).

The shallowness of a lagoon and the flatness of its bed could result from detrital fill or by continuing hydroisostatic rebound – or both combined. Detritus from reef and land erosion is present in every lagoon but an enormous volume would be needed to fill them to sea level in the relatively short period of their existence. Erosion would mostly accompany storms – wave abrasion of reef, and land erosion when usually dry alias flow during heavy rain.

Uplift is suggested as the main cause of shallow-water lagoons. Emergence , probably related to hydroisostatic rebound , has been firmly established for both Upolu and Savaii. It could still be active but at a rate that is presently being outpaced by rising sea which, for Samoa, is three millimetres annually.

BEACHROCK.

Storm erosion of Tafagamanu Sand plus the addition of new sand by wave abrasion of the coral reef (and parrot fish grinding up live coral to extract the algae and protein) have built to-day's beaches but, quite often, access to the lagoon is obstructed by bands of dense, slippery rock deeply pitted at surface. This, previously called coquina, has been re-named beachrock. It occurs in the intra-tidal zone between a beach and lagoon.

Coral sand is composed of calcium carbonate and, like limestone, is slowly soluble in cool fresh water. Fresh water of a Ghyben-Herzberg Lens on seeping through Tafagamanu Sand will become charged with calcium carbonate which, on entering the tidal zone, will be precipitated by the chloride ion of the salt water thereby cementing unconsolidated sand grains into beachrock.

The width of the tidal zone and consequently that of the beachrock outcrop varies with the slope of the beach. When steep, 3 or 4 narrow, closely spaced bands of rock will be exposed with falling tide, each band being progressively higher towards the shoreline. A fine example of this can be seen at Faga, east coast of Savaii.

When slope is gentle, the outcrop will be wide – as at Satuiatua, south Savaii, where two broad, parallel bands of beachrock have been mistaken for roads. They are 17 metres apart, slope gently seawards, with the more seaward band 30cm higher than the landward band. This is puzzling as the intra-tidal zone where beach rock forms encroaches landwards with rising sea. Carbon dating of the two bands might help resolve this enigma but would be costly and possibly inconclusive as both bands would consist of cemented Tafagamanu Sand with only a minor content of dateable younger coral fragments.

EMERGENCE versus SUBSIDENCE

The relationship between rising sea and Samoa's two main islands needs clarification. Some scientists suggest Upolu is sinking whereas the writer believes Savaii could be slowly rising. Isostatically, the islands are unlikely to differ. They are neighboring pinnacles of an enormous volcanic edifice extending the length of the Samoan Archipelago and, apart from Savaii's intense volcanism, their mid to recent Holocene histories have been identical. Both developed coral growth between 7000 and 5000 years ago and both reacted to the hydroisostatic rebound which raised Tafagamanu Sand along coastal sections of each island. Emergence may have slowed or stopped over the last several thousand years but a reversal to subsidence in Upolu seems highly unlikely.

Emergence would temporarily delay the effects of rising sea but climate is warming and, unless brought under control, future levels will make Samoa's coastal areas vulnerable to sea invasion and extreme weather events that could be more devastating in damage and loss of life than future volcanic eruptions.

APPENDIX

COMPOSITION OF THE EARTH

The earth consolidated from a cloud of hot gas some 4.6 billion years ago and now consists of a core, mantle and lithosphere, each with distinct layers.

The inner core is a sphere 1300km in diameter extremely hot (4300°c) consisting predominantly of iron. It is kept solid because of enormous confining pressure. The outer core, 2215km thick is fluid iron with slowly converting currents creating the earth's magnetic field.

The 2850km thick mantle is entirely basaltic, the lowermost 2200km being solid then a transition zone to the semi-molten material of the upper mantle. This, the asthendsphere, is all-important in plate formation and is discussed later. The uppermost layer of the mantle is again solid and varies considerably in thickness from 70-80km under continents to very thin or absent under the oceans.

The lithosphere consists of the uppermost solid layer of the mantle and the crust, the crust varying considerably in rocktype and thickness between continental and oceanic plates.

PLATES

The earth's 16 major plates vary in rocktype, size and thickness an move in different directions at different rates. Oceanic plates are composed entirely of basalt that has slowly welled up along rifts in the mantle and spread over the ocean floor. Continental plates are those with locked-in continents, either completely surrounded by or bounded on one side by oceanic basalt. Plate thicknesses ranges from 5km or less for oceanic plates to 150km for continental plates. Movements of the oceanic plates is as much as 9cm yearly. Continental plates with deep roots move much more slowly.

Plates can slide by one another, move away from one another or collide to create transform, divergent or convergent plate boundaries. Divergent and convergent boundaries are a big part of this Samoan story so need explaining.

Divergent boundaries (originally called constructive plate margins – or much more descriptively “zones of ocean floor spreading”) are best explained by illustration (fig.13)

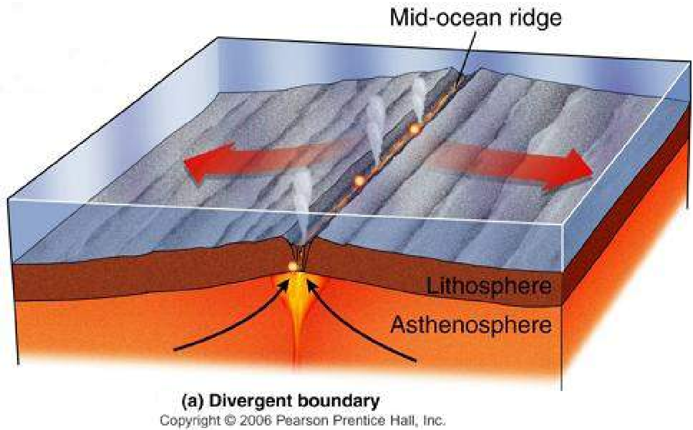


Figure 13: Divergent Plate Boundary

Divergent currents of upper mantle basalt rise, stretching and rupturing the overlying crust. Semi-molten magma slowly wells upwards to fill the gap and build a high mid-ocean ridge with a deep central rift.

This is the zone of divergence where oceanic plates start moving in opposite directions. The East Pacific Rise is the divergent plate boundary where the westerly moving Pacific Plate and the easterly moving Nazca, Cocos and Juan del Fuca plates are born. Samoa lies near the western margin of the Pacific Plate.

Convergent boundaries (previously called destructive) form when a plate of heavy oceanic basalt collides with and plunges below a plate of continental rocks or sometimes a plate of younger, less dense oceanic basalt (fig 14). This is called subduction whereby a). the edge of the lighter plate will be dragged down to form a deep ocean trench; b) friction of one plate grinding below another will generate sufficient heat to melt the overlying, usually silicious rocks resulting in chains of volcanoes over subductions zones eg. the Pacific's "Ring of Fire" and c) plates lock and, on release, cause earthquakes. The subducting plate will be re-absorbed into the hot asthenosphere to enter a new cycle of birth, carriage and destruction.

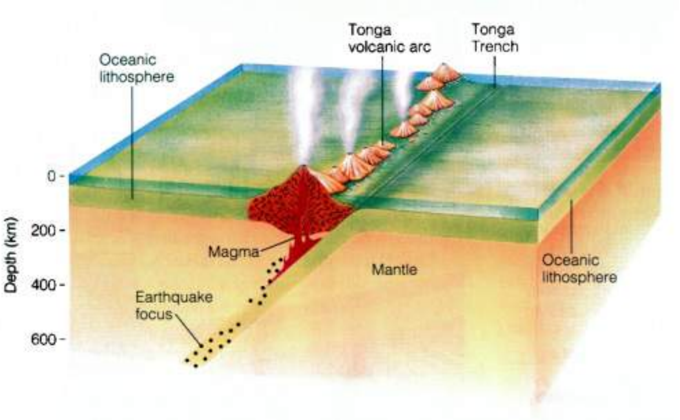


Figure 14: Convergent Plate Boundary

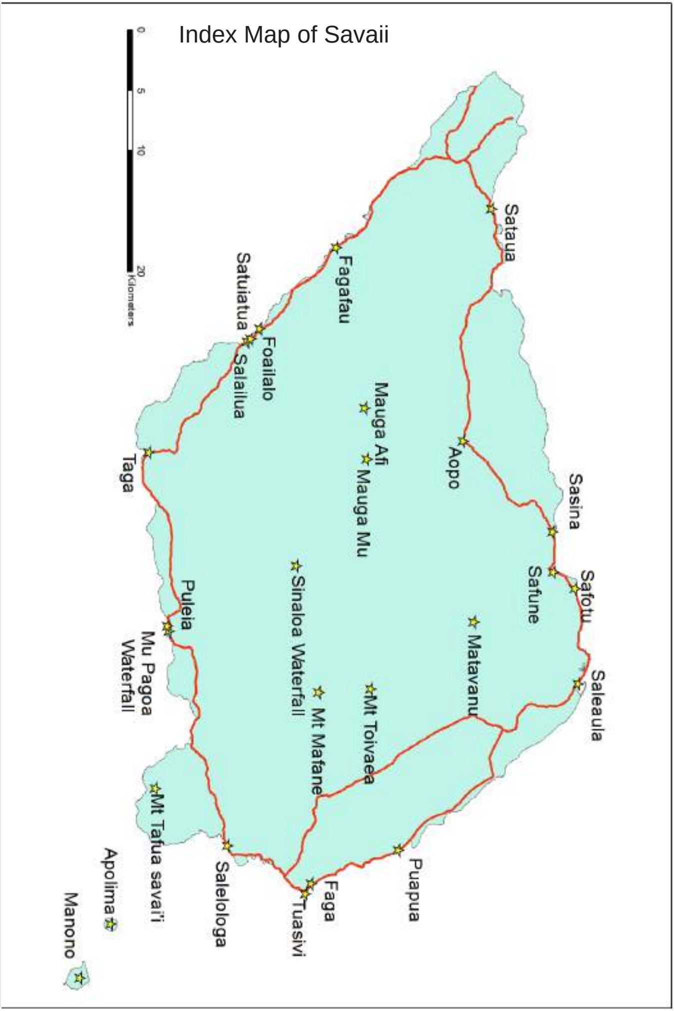
PALAEOMAGNETISM

Convecting currents of fluid iron in the outer core make the earth act like a giant magnet with north and south magnetic poles roughly corresponding to the north and south geographic poles. Over time the magnetic poles wander around their geographic poles causing the earth's magnetic field to slowly change. And over very irregular time periods the convecting currents slow, stop and reverse causing the earth's polarity to reverse.

Timewise these reversals have varied from about 20,000 years to 23 million years but average about 400,000 years. The earth's present N-S field has lasted over the past 750,000 years but is weakening, indicating an approaching reversal.

Any rock containing iron which forms to-day will be magnetized with iron minerals pointing to to-day's north magnetic pole and, once magnetized, this signature will be fossilized in the rock for future time. Iron minerals are a dominant constituent of all basalts, those of Fagaloa age (ie – hot spot origin) showing reverse polarity whereas Salani, Mulifanua, Puapua and Aopo volcanic show normal (to-day's) polarity.

Index Map of Upolu


Index Map of Savaii
0
5
10
20
Kilometers
Sataua
Fagafau
Satuiatua
Foailalo
Salailua
Mauga Afi
Mauga Mu
Aopo
Sasina
Safune
Safotu
Taga
Sinaloa Waterfall
Matavanu
Puleia
Mu Pagoa
Waterfall
Mt Mafane
Mt Toivaea
Saleaula
Mt Tafua savai'i
Salelologa
Faga
Tuasivi
Puapua
Apolima
Manono

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