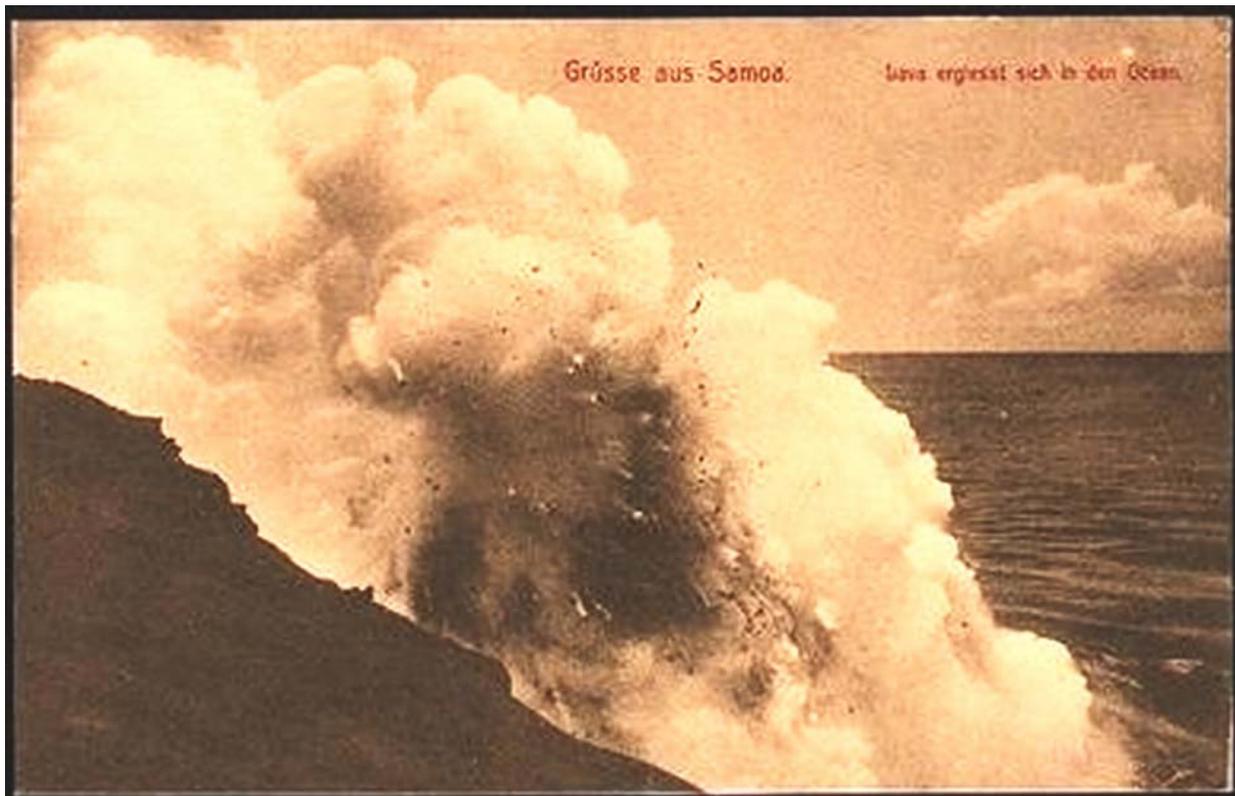


EU EDF 8 – SOPAC Project Report 59
Reducing Vulnerability of Pacific ACP States

SAMOA TECHNICAL REPORT – REVIEW OF VOLCANIC HAZARD MAPS FOR SAVAI'I AND UPOLU

July 2006



Historical Postcard of Matavanu Eruption 1905-1911 – Lava enters the sea

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Important Notice

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EXECUTIVE SUMMARY

Both main islands of Samoa, Savai'i and Upolu need to be considered as potentially volcanically active. The most recent eruptions in historic times happened on Savai'i in 1905-1911, 1902 and 1760 (estimated). Though detailed volcanic studies and dating of volcanic events are very limited there is evidence for repeated volcanic activity on both islands since the time of human occupation of the islands marked by prominent and fresh appearance of tuff cones as Tafua (= fire mountain) Savai'i, the island of Apolima, Tafua Upolu and offshore Cape Tapaga.

This report examines the volcanic risks for both islands and defines for disaster management considerations potential eruption scenarios based on eyewitness accounts of previous eruptions, geological field evidence, remote sensing information and experiences from similar volcanoes. A detailed timeline of events, potential impacts and required emergency response activities are listed for the five potential eruption types (1) long-term lava field (2) short-term spatter-cone (3) explosive phreatomagmatic (4) explosive scoria-cone and (5) submarine flank collapse.

Given the nature of volcanism in Samoa with hundreds of individual “one-off” volcanoes scattered along zones of structural weakness within the Savai'i – Upolu Platform – predicting the exact location of future eruption centres is impossible. At the current stage of knowledge a presentation of a volcanic hazard map is inadequate and would require additional baseline studies to statistically define recurrence intervals and areas of higher volcanic activity. Taking these limitations into account, maps showing the relative potential for new eruption vents on Upolu and Savai'i are derived from geomorphologic features.

To improve our understanding and management of the volcanic risks of Samoa, suggestions for achievable future work are listed and prioritised. These recommendations include geological/volcanological baseline studies (e.g. dating/detailed analyses of past events, rock chemistry, volcano structure); installation of early warning and monitoring network (e.g. permanent GPS, seismometers); and disaster preparedness and volcanic crisis response planning.

ACKNOWLEDGEMENTS

The European Commission provided funding for this project task under the framework of the SOPAC/EU Reducing Vulnerability of Pacific ACP States Project. The professional time of Drs Shane Cronin and Karoly Nemeth from Massey University, New Zealand, was provided in-kind.

The work was carried out in close cooperation with the Meteorology Division of the Ministry for Natural Resources, Environment and Meteorology (MNREM) with managerial support from Ausetalia Titimaea and Sagato Tuiafiso. Samuelu Ta'ape (Geology Section), Shaun Williams (Geophysics Section) and Filomena Nelson (Disaster Management Office) contributed actively to the findings of this report.

Orthophotos and topography layers used in this report were kindly provided by the Mapping Section of the Lands & Survey Division, MNREM.

1 INTRODUCTION

In his opening address at the SOPAC 34th Annual Session in Apia 2005, Hon. Faumuina Liuga, Minister of Works, Transport and Infrastructure recalled the historical eruptions on Savai'i highlighting the persisting risk of volcanic activity for the population of Samoa. He emphasised in particular the need for adequate monitoring and warning services. During the 2nd multi-stakeholder held meeting in Samoa in December 2003, the SOPAC/EU *Reducing Vulnerability of Pacific ACP States* Project was requested to review the volcanic hazard map of Savai'i produced by Taylor & Talia 1999 and revised by Cronin et al. 2001b.

Savai'i, the biggest and westernmost island of the Samoan group with a population of some 50 000, showed the most recent volcanic activity. Three major eruption phases took place in historic times, which produced lava flows that destroyed several coastal villages: namely the Matavanu eruptions 1905 to 1911; some smaller eruptions at Mauga Mu in 1902; and at about 1760 the eruptions at Mauga Afi with excessive lava flows covering vast areas along the north coast of Savai'i. Also, throughout the Holocene, the youngest period in Earth's history, both big islands of Samoa – Upolu and Savai'i – have been volcanically active with evidence for several active eruption centres within the last few thousand years. Though the available age date currently does not allow establishing reliable recurrence intervals for volcanic active periods, volcanism in Samoa is unlikely to have ceased, and both big islands need to be considered as potentially active.

This report elaborates on the existing volcanic risks for both islands; and by establishing likely scenarios of volcanic crises, provides guidance for disaster management operations.

2 PROJECT OBJECTIVES

(from original contract):

- 2.1 Project task WS 3.5.6 Review of Savai'i volcanic hazard map based on:
 - a. Taylor, P.W., Talia, L. 1999: Volcanic hazards assessment of Savai'i, Samoa. SOPAC Technical Report 295. 26pp + Map
 - b. Cronin, S.J., Taylor, P.W., Malele, F., 2001: Final report on the Savai'i volcanic hazards project, Samoa. SOPAC Technical Report 343. 34 pp.
- 2.2 The review shall be carried out together with staff of Samoa Geology, MNREM and Michael Bonte-Graptin, SOPAC/EU Risk Assessment Specialist, during a 1 week visit to Samoa
- 2.3 Field tasks are to include geological interpretation of the volcanic deposits exposed on Savai'i. Sites of the most recent eruptions will be visited, including eruption centres of the 1905-1911 and 1760 eruptions. Other supplementary sites are to include representative locations for the full range of volcanic processes possible on Savai'i, including scoria cones

(exposed in east Savai'i) and phreatomagmatic centres (such as Tafua Savai'i, exposed in west Savai'i).

- 2.4 Office-based tasks before and after the field visit are to include a review of the literature pertaining to past eruption descriptions and geological mapping on Savai'i and similar types of volcanic structures.
- 2.5 Tasks in Apia will include the acquisition of relevant available GIS layers and remote-sensing data including ortho-rectified images.

3 TASKS COMPLETED

- 3.1 Visit to Samoa, 4-12 February 2006.
- 3.2 Field work in Savai'i was carried out with Samuelu Ta'ape (Geology), Mr Shaun Williams (Geophysics) and Ms Filomena Nelson (NDMO). February 5-8 were spent in the field, although rainstorms and flooding disrupted much of the planned field visits (Figure 1). A range of sites were visited to encompass the range of eruption types known from this volcano, including:
 - a. Long-term lava-flow eruptions: 1905-1911 Matavanu flows, AD1760 lava flows.
 - b. Short-term, small-scale spatter cone eruptions: 1902 Eruption, Seuseu crater and other west Savai'i cones.
 - c. Short-term, small-scale lava-water littoral explosions: South Savai'i lava coastline Taga-Gatavai.
 - d. Large-scale magma-water interactions and explosive eruptions: Tafua Savai'i, East Savai'i.
- 3.3 A review of geological and volcanological literature was carried out in order to place the previous work in context with the range of theories for development of the Samoan chain. A list of references consulted is included in this report.
- 3.4 A revised hazard assessment of volcanism in Savai'i and also Upolu was developed in context with the review of the Savai'i Hazard map, taking into account a reassessment of the literature (see Section 4).
- 3.5 Recommendations for future follow-up activities were derived and prioritised through meetings and discussions with MNREM staff whilst in the field and during meetings in Apia (see Section 5).



Figure 1: Field party visiting the Matavanu lava field – continuous rainfall hampered intended field visits.

4 REVIEW OF SAVAI'I VOLCANIC HAZARD MAP

4.1 Background

The islands of Savai'i and Upolu are the western-most and largest islands of the Samoan group and have experienced a long period of volcanism, with the oldest deposits thought to be >2 million years (Kear and Wood, 1959; Keating, 1992). Volcanism on both islands appears to be focussed along broad lineations, which variously mark rift zones or in some cases deep-seated faults.

Eruption locations, as marked by lava-flow sources and volcanic cones are mostly concentrated along a broad east-west oriented zone, which is clearest on Upolu. On Savai'i the pattern of vent sites is more complex, with up to five rift-zones postulated by some authors (Kear and Wood, 1959; Keating, 1992).

Few recent detailed geological studies of Samoa have been undertaken. The most comprehensive geological mapping (at 1: 400 000 scale) was conducted in the 1950's (Kear and Wood, 1959). Little specialist volcanological work has been published or completed since and thus limited data exist to constrain age and frequency of past eruptions.

4.2 Upolu Island

Although Upolu Island does not have the youngest of the mapped Holocene volcanic rocks present in the Samoan Group (Kear and Wood, 1959; Keating, 1992), it has several areas mapped as early Holocene in age (> 5000 years) and several volcanic features that are fresh in appearance. The prominent cone in western Upolu, named Tafua Upolu, may be linguistic evidence for activity since people were present. The word Tafua is a cognate of Tofua, which means *fire mountain* – used for the active volcanic island in Tonga, and Tavuyaga (in archaic Fijian) used for a young volcanic cone on Taveuni, Fiji (Cronin and Neall, 2001). Notably the Tafua Savai'i in east Savai'i, is thought to be slightly older than 610 ± 60 years B.P. (Cronin et al., 2001b). Other direct evidence of late Holocene volcanism on Upolu during the time of human occupation comes from a little-known published radiocarbon age of 1915 ± 65 yrs B.P. (NZ377; Grant-Taylor, and Rafter, 1962). This date provides a maximum age limit on a tuff cone – or highly-explosive phreatomagmatic eruption from a vent just offshore of Cape Tapaga, east Upolu. Similarly – late Holocene volcanism has also been reported and described from Tutuila, farther eastward along the same major crustal structure (e.g., Keating, 1992).

This evidence from different locations on Upolu and farther east, imply that despite the absence of historical activity, volcanism on Upolu is by no means extinct, and volcanic hazards on this island should be considered with the same degree of importance as with those on Savai'i. Hence, the remainder of this report will consider the potential volcanic hazards on both of the main Samoan islands.

4.3 Volcanic vent-location map

The type of volcanism on Upolu and Savai'i is known as “monogenetic”, that is, each eruption location is normally only active once and the subsequent activity is located elsewhere. Hence, the islands are marked by hundreds of “one-off” volcanic cones or lava fields (e.g. as noted from Taveuni in Fiji; Cronin and Neall, 2001). The implication of this process is that it is almost impossible to predict the location of the next eruption site with certainty. Large datasets of event age and location data are needed to statistically constrain forecasts of future activity and hence create effective hazard maps (e.g. Cronin et al., 2001). At best – with the data at hand – a broad map of potential vent areas is the most reasonable approach.

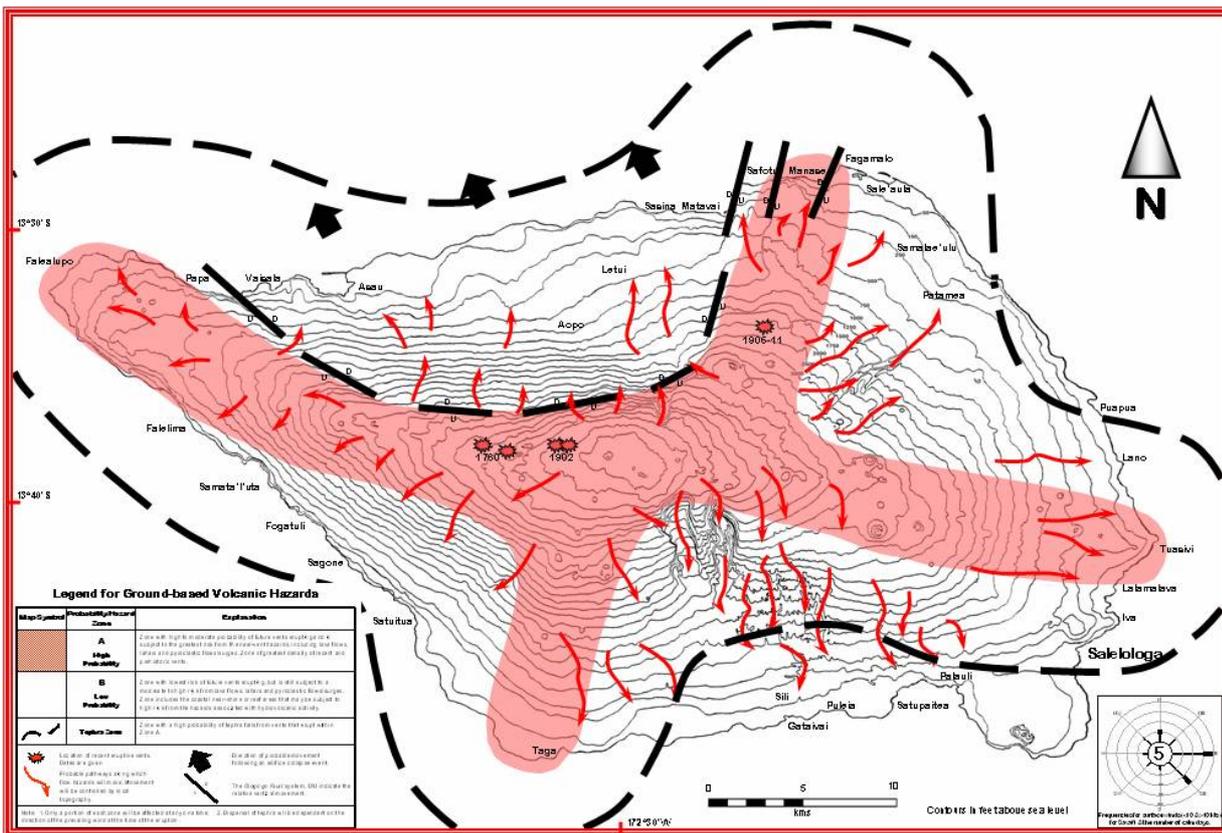


Figure 2: Hazard map revision as presented by Cronin et al. (2001b).

The hazards map for Savai'i proposed by Taylor and Talia, (1999) and updated by Cronin et al. (2001b) takes the approach of identifying all of the main active arms of the rift (Figure 2). It tries to overlay an impression of where the main vent locations could be with an indication of where lava flows are likely to descend into populated areas. Because of these two factors, the map has been considered confusing by most Samoan users. In addition, it has not been well adopted into public awareness campaigns.

Here we question the usefulness of a map to display hazards for this island. Since the location of the next potential eruption is so poorly known, the best we can propose is a map showing areas that have the greatest chance for new volcanic vents to form. The basis of these maps is a re-analysis of the structural geology of Savai'i and Upolu, particularly taking into account recent findings of the nature of the overall crustal structure in the Samoa region gained from studies of the surrounding ocean floor geology (Hill and Tiffin, 1993; Keating et al., 2000). On the vent locations map proposed (see Appendices 1 & 2), we identify the main structural lineations that appear to have controlled Pleistocene and Holocene volcanism on the two islands. This structure is particularly complicated on Savai'i (Appendix 1), where an en-echelon series of lineations/rifts along the central E-W axis is cut by a large NW-opening curved fault structure, the extent of which extends below sea level (Hill and Tiffin, 1993).

The zonation of potential vent locations is derived from geomorphologic inferences of the underlying structural geology of the islands. The most obvious features are the distribution of volcanic cones. These areas of cone development mark zones of weakness and faults where magma has risen in the past (e.g., Walker, 1987; Caracedo, 1994). The cones are not an absolute guide, since many lava-field eruptions may just form from fissures, leaving little geomorphic evidence of the vent location. In addition, some of the cones/vents may form downslope of the original rise point of magma – with magma transferred laterally through subsurface rift zones – such as on Etna volcano or Hawai'i (e.g. Kilauea Volcano).

Given these limitations we have derived a three-colour zonation of relative potential for new eruption vents on Upolu and Savai'i:

- i. **Red zone** – highest probability for new vents. This zone only occurs on Savai'i and is located along a major curved fault system, open and downthrown to the NW. This major system has been identified by many authors and was used as the highest hazard zone of the map by Taylor and Talia (1999). Along this zone is the most active tectonic movement and the locations of all the historic eruptions (1760, 1902, 1905-11) are known.
- ii. **Orange zone** – medium probability for new vents. This zone encompasses the main central structural rift of both Savai'i and Upolu. This represents the structural axis of the Samoan islands (Kear and Wood, 1959; Keating, 1992) and is sub-parallel to crustal stresses identified between the northern Tonga-Samoa area in submarine geology studies (Hill and Tiffin, 1993). The structure is offset between Savai'i and Upolu – demonstrating a typical en-echelon form (of sub-parallel lineations offset by lateral faults). It is possible that the most active part of the fissure system is the location of lateral stress-transfer from the central Savai'i fissure to the Upolu fissure. Along this line are the late Holocene (<2000 years BP) cones of Tafua Savai'i (Cronin et al., 2001b), Apolima, Manono and Tafua Upolu. In addition, at the eastern-most end of the Orange zone on Upolu there is another late Holocene (1915 yrs BP; Grant-Taylor and Rafter, 1962) eruption centre at Cape Tapaga.
- iii. **Yellow zone** – low probability of new vents. In these zones, there are signs of previous activity demonstrated by cones of mainly Mulifanua and older age (Kear and Wood, 1959). These possibly represent older rift/fissure systems that are assumed to have ceased, hence future eruptions in these areas are unlikely, although not impossible, since the crustal weaknesses of these areas will still be present.
- iv. Remainder of island – very low probability of new vents. Despite having limited current knowledge and understanding of the structure and historic development of Savai'i – the features as explained would imply that formation of vents outside the three coloured areas is highly unlikely – although not fully impossible.

Identifying more specifically the potential location of volcanic eruptions inside these zones will only be possible by examining the precursory seismic or other activity associated with oncoming eruptions. For this, a greater number of well-spaced seismographs are required. There is only one 3-component seismograph currently operated in Samoa, which will probably provide days to up to weeks of warning of an impending eruption (such as in 1905); but it will be a poor guide to eruption location. Having a network of stations installed around both islands will allow a 3-d positioning of earthquakes associated with rising magma and eruptions, thus allowing the chance to potentially pinpoint sites of activity and judge the onset of eruptions through tracking the rise of earthquake loci through the crust to the surface.

By comparison to eruption location, the styles and processes of eruptions in Samoa can be predicted with greater confidence from interpretation of deposits and by comparison to similar volcanoes such as Hawai'i, Taveuni (Fiji) and the Canary Islands.

4.4 Potential eruption scenarios, hazard processes and emergency management considerations

Eruption events are made up of several phases over sometimes long periods. During eruption events, there can be different types of processes operating in isolation or sometimes even in concert. Each of the processes (e.g. lava flows, ashfalls, pyroclastic surges, littoral explosions, etc) poses different kinds of hazards to the community. However, rather than considering each volcanic process in isolation, it is more useful to examine what range of processes would occur in typical volcanic events. In this section a series of brief volcanic event scenarios will be described (Table 1). The physical nature of these is based upon field studies as well as remote-sensing evidence of past volcanic structures and deposits on Savai'i and Upolu. This information is strengthened by considering literature data from Samoa and beyond; and most importantly an analysis of the witnessed historic eruptions of Savai'i.

Table 1: Potential eruption types on Upolu and Savai'i.

Eruption/event type	Examples	Duration	Area fully destroyed	Area partly damaged	Potential human impacts
1. Long-term, lava field eruptions	1760, 1905-11	Many years, can be decades	10 to >200 km ²	<10 km ²	Low potential for loss of life, but permanent damage to property and farmland
2. Short-term spatter-cone eruptions	1902, Seuseu W-Savai'i area	Days to weeks	2-10 km ²	10-50 km ²	Low potential for loss of life; localised damage to property and farmland
3. Explosive phreatomagmatic eruptions	Tafua Savai'i	Weeks to months	10-30 km ²	50-100 km ²	Moderate potential for loss of life, localised damage to property and farmland
4. Explosive scoria-cone eruptions	Tafua Upolu	Weeks to years	10-30 km ²	50-200 km ²	Low potential for loss of life, localised damage to property and farmland
5. Submarine flank collapse	S-Savai'i	Several hours	unknown	unknown	High potential for deaths through associated tsunami

4.4.1 Long-term lava field eruptions

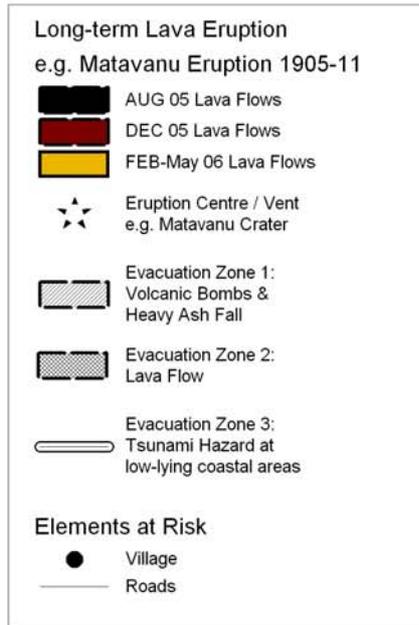
The best example of this type of scenario on Savai'i is the 1905-1911 Matavanu eruption (Figure 3). Many descriptions of parts of this eruption and its effects are available in both English and German (e.g., Sapper, 1906; Jensen, 1907; Anderson, 1910). These descriptions give rise to a scenario of events and hazards (Table 2).



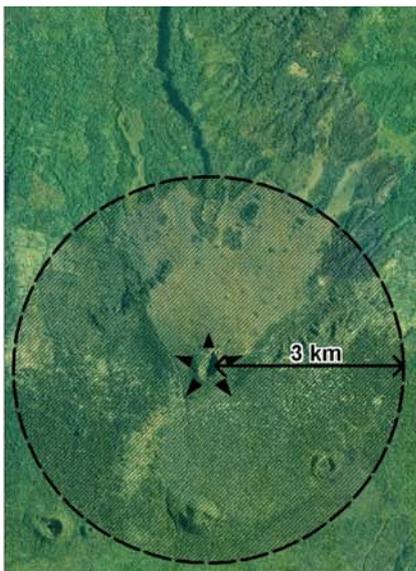
Figure 3: Field party examining the features and extent of devastation resulting from the 1905-1911 lava flow field eruption.

Table 2: Summary eruption scenario of the 1905-1911 eruptions derived from volcanic literature and historic reports.

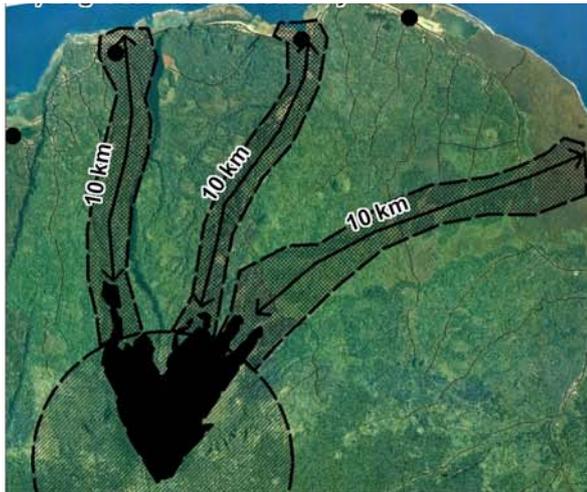
Timeline	Events	Impacts/Hazards	Actions required
0-10 days	Earthquakes detected on seismographs – very few felt by people.	None	Identification of eruption zone. Public warning. Installation of volcanic monitoring network – seismic.
10-20 days	Eruption starts, producing small-scale explosions to build up one or more spatter cones.	Vent area – burial of c. 200 m radius by spatter cone. Volcanic bombs thrown out to 1.5 km radius – common in 1 km from vent. Ashfall several cm thick in areas up to 3 km away.	Evacuation of people in a 3 km radius of vent. Evaluation of lava flow pathways and potential new hazard areas. Evaluation of wind direction and ash-fall hazards. Public information. Regular aerial monitoring of eruption.
20-30 days	Lava flows begin – either from an opening of the crater (wind direction or collapse influenced) or from the base of the cone.	Burial by lava of areas up to 3 km from source. Minor or no ashfall.	Evacuation of lava flow pathway and a down-slope projection from the pathway up to 10 km from the flow front. Regular aerial monitoring to predict lava paths.
30-90 days	Lava flows reach the coast on several fronts, begin filling lagoon areas.	Burial by lava of major areas, >10 km from source. Littoral explosions where lava traps beneath in lagoons – exploding blocks to up to 100 m from explosion site. Production of sulphur dioxide (SO ₂) gases and aerosols – known as vog (volcanic fog).	Evacuation of all lava pathways and areas within 1 km of the lava entry to the sea. Monitoring of wind direction for volcanic gas/vog emissions. Regular aerial monitoring of flow entry points and flow margins for breakouts.
3 months – several years	Lava flows continue underground through tubes and exit at the sea. Large lava blisters may form near coast and suddenly collapse. Lagoons fill and lava spills over reefs. Lava platforms collapse into the sea. Eruption intensity waxes and wanes – with periods of several months having little activity, followed by resurgence of activity.	Burial of new areas by lava as flows break-out from sides of main channels. Tsunamis generated in areas up to 10 km of lava ocean entry as lava platforms collapse into the sea. Vog of variable intensity dispersed with wind – crop damage. Minor ashfalls up to 5 km from vent and from ocean entry of lava on rare occasions – crop damage and respiratory impacts.	Evacuation of all areas up to 1 km from sides of lava flows. Regular aerial monitoring of flow propagation and potential lateral breakouts. Continued volcanic monitoring with seismographs and wind/weather monitoring for vog/ash forecasts. Evacuation of near-coastal areas within 10 km of lava entry point to protect from tsunami hazard. Regular public briefings.
After 1 – several years	Eruption slowly diminishes in intensity, lava flows diminish, lava tubes empty, vog emission decreases and eventually eruption gradually ceases. After 12 months of no activity, eruption has finally ceased.	Reduced intensity impacts of hazards from all types, but possible resurgence of activity for short bursts.	Ongoing actions as above, winding down following 12 months of inactivity.



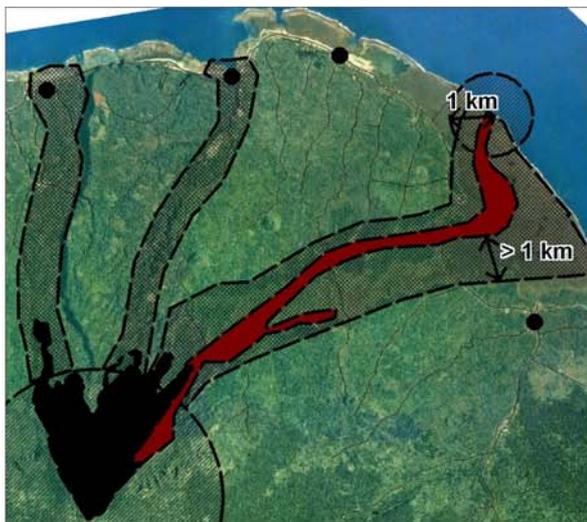
a) Beginning of Explosive Activity



b) Beginning of Lava Flow Activity



c) Lava flow reaches coast



d) Underground lava flows exit at sea – tsunami risk

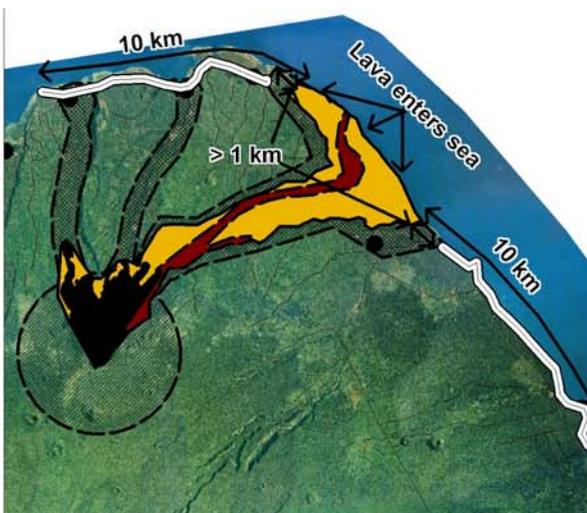


Figure 4: Example for delineation of evacuation zones for long-term lava flow eruptions a) after identification of eruption centre protect population from heavy ashfall and volcanic bombs (often not required, since most vents are in remote areas); b) with beginning of lava flow activity evacuate population within the pathway of the lava flow; c) risk of littoral explosions when the lava flow enters the sea; and d) local tsunami risk due to lava platform collapsing into the sea.

4.4.2 Short-term spatter-cone eruptions

This style of eruption may precede the major lava flow events, but in many cases these are eruptions of only small volumes of magma, that never produce more than a spatter cone or small lava flows. Many examples of these kinds of events are present on Savai'i and Upolu, with easily visited sites in the Seuseu area of West Savai'i (Figure 5). The 1902 eruption on Savai'i was a good example of this type. From this data a scenario has been prepared (Table 3).



Figure 5: Field party examining the internal features of a quarried spatter cone in the Seuseu area.

4.4.3 Explosive phreatomagmatic eruptions

These styles of eruptions are arguably of greatest potential hazard to life in Samoa. Due to their rapid acceleration to explosive phases, they have the potential to catch local populations unawares. Also these types of events are far more explosive than the eruption types described already. It is well known that the interaction of magma and water induces a highly explosive fuel-coolant interaction (e.g., Wohletz, 1986; Zimanowski, 1998). This generates large and highly energetic eruptions.

Table 3. Summary of eruption scenario of a short-term spatter-cone eruption derived from volcanic literature and historic reports of the 1902 event.

Timeline	Events	Impacts/Hazards	Actions required
0-10 days	Earthquakes detected on seismographs in 1902 – several were felt by people.	Fear/unsettling of the population.	Identification of eruption zone. Public warning. Installation of volcanic monitoring network – seismic.
10-20 days	Eruption starts, producing small-scale explosions to build up one or more spatter cones.	Vent area – burial of c. 200 m radius by spatter cone. Volcanic bombs thrown out to 1.5 km radius – common in 1 km from vent. Ashfall several cm thick in areas up to 3 km away.	Evacuation of people in a 3 km radius of vent. Evaluation of lava flow pathways and potential new hazard areas. Evaluation of wind direction and ash-fall hazards. Public information. Regular aerial monitoring of eruption.
20-30 days	Lava flows begin – either from an opening of the crater (wind direction or collapse influenced) or from the base of the cone.	Burial by lava of areas up to 3 km from source. Minor ashfall.	Evacuation of lava flow pathway and a down-slope projection from the pathway up to 10 km from the flow front. Regular aerial monitoring to predict lava paths. Regular public information updates.
1-3 months	Variable levels of activity, small flows from other sides of the cone, cone growth and inward collapse, small-scale explosions, finishing suddenly or gradually winding down over several months.	Burial by lava of minor new areas Minor ashfall.	Maintenance of evacuation areas. Regular aerial monitoring. Wind/weather monitoring. Regular public information updates. When eruptions have ceased for >6 months, wind down operations and evacuation restrictions.

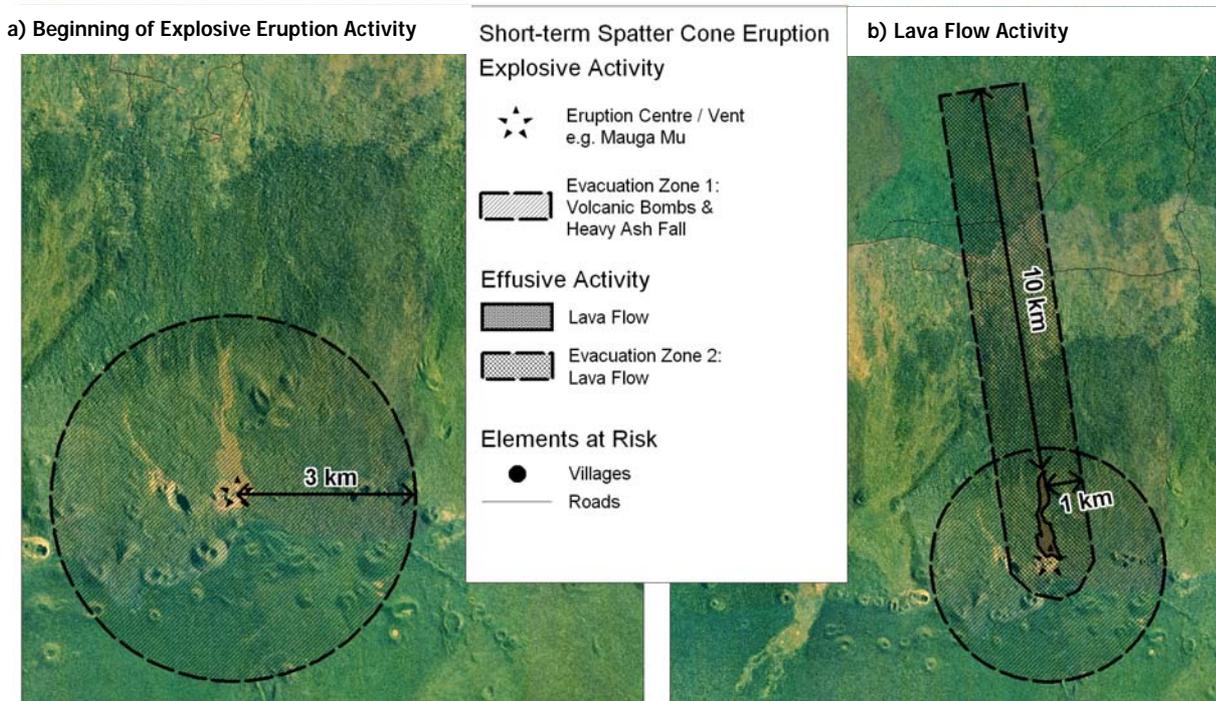


Figure 6: Examples for evacuation zones for short-term spatter cone eruptions. a) After identification of eruption centre protect population from heavy ashfall and volcanic bombs (often not required, since most vents are in remote areas); and b) with the beginning of lava activity, evacuate population from within the pathway of the lava flow.

Typically there is an ideal ratio of magma:water, too much water dampens explosivity, and too little results in also a lower-energy eruption and transition to more normal spatter or lava-flow eruption. The other feature about these eruptions is the generation of so-called pyroclastic surges (Moore, 1967) – rapidly expanding mixtures of gas/ash/steam that explode outward from the eruption site along the ground or water surface. These are rapidly moving (>30 m/s) and destroy most things in their path. They offer the greatest danger to life, of all the Samoan eruption styles. A good example of this type of event is demonstrated by the Tafua Savai'i complex in eastern Savai'i. In addition, a recent example of this type of eruption occurred in the Southwest Pacific region, at Ambae volcano in Vanuatu, over the period December 2005 – January 2006 (Nemeth et al., in press). The following scenario (Table 4) is based upon a geological interpretation of the Tafua-Savai'i complex (Cronin et al., 2001b); the recent Ambae eruption (Nemeth et al., in press); and other historical examples of these types of events worldwide (e.g., Zimanowski, 1998).

Table 4: Summary of eruption scenario for an explosive phreatomagmatic eruption (near-shore/offshore).

Timeline	Events	Impacts/Hazards	Actions required
0-10 days	Earthquakes detected on seismographs – some felt by people nearby one or two days before eruption.	Fear/unsettling of the population.	Identification of eruption zone. Public warning. Installation of volcanic monitoring network – seismic.
10-12 days	Eruption starts, often in underwater areas (e.g. lagoons or nearshore). Explosions begin immediately to penetrate water surface, producing vertical steam-rich ash columns up to 2 km high and laterally-moving pyroclastic surges. Most eruption occurs underwater and vent is drowned.	Volcanic bombs thrown out to 500 m radius. Pyroclastic surges moving at >30 m/s laterally out up to 500 m from the vent. Ashfall several cm thick in areas up to 3 km away. Small seiche-like tsunami waves formed as eruption breaks surface and as surges are generated, affecting areas up to 2 km from source. Volcanic gas/vog may form.	Immediate evacuation of people in a 3 km radius of vent. Evaluation of wind direction and ash-fall hazards. Public information updates. Regular aerial monitoring of eruption.
12-20 days	Island of volcanic debris is constructed around the vent area, reducing access of water – since some water still accesses the vent – eruption intensity increases with larger surges and more ash-rich columns.	Volcanic bombs thrown out to 2 km radius. Pyroclastic surges moving laterally at >30 m/s laterally out up to a 2 km radius, structures and crops in their paths destroyed. Ashfall several cm thick in areas up to 5 km away – minor ashfall can occur up to 10 km away. Small tsunamis continue.	Expansion of evacuation zone to a 5 km radius. Regular aerial monitoring of eruption. Monitoring of wind direction/strength to provide ashfall forecasts. Regular public information updates.
20 days – 3 months	Activity wanes as magma supply exhausted or when island fully formed around vent to block water access. In latter case, eruption intensity decreases and spatter or lava flow activity begins as described in scenarios 4.4.1 and 4.4.2.	As above, with decreasing areas affected. Onset of spatter/lava activity coincides with cessation of surges and significant ashfall. Lava flow onset will begin to cover nearby areas, interaction with seawater may produce vog.	Maintenance of evacuation areas. Regular aerial monitoring. Wind/weather monitoring. Regular public information updates. When eruptions have ceased for >6 months, wind-down operations and evacuation restrictions.

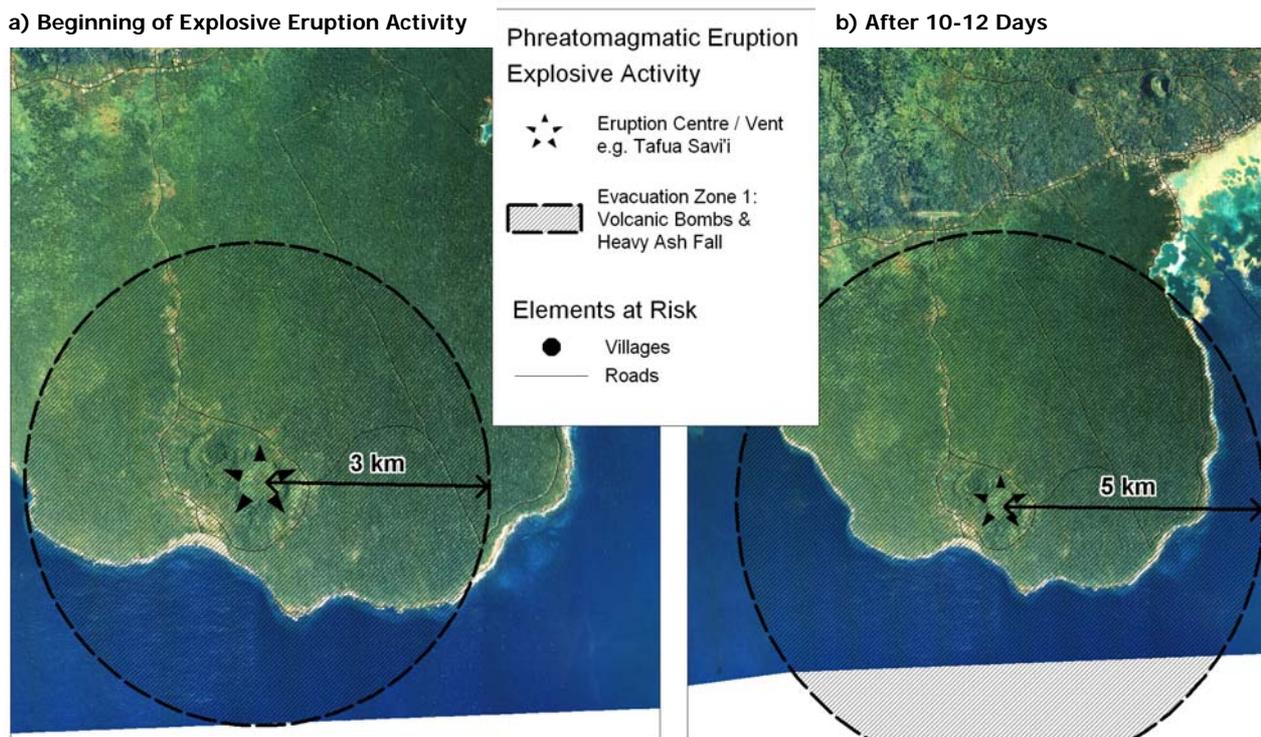


Figure 7: Examples of evacuation zones for violent phreatomagmatic eruptions, which pose the biggest threat for loss of life. They can occur close to villages along the coast and show the highest explosivity of all eruption types found in Samoa.

4.4.4 Explosive scoria-cone eruptions

The explosivity of all eruptions depends in the first instance on the gas content of the magma when it reaches the ground surface. For the basaltic magmas typical of Savai'i and Upolu (Kear and Wood, 1959), gas escape occurs well before the magma reaches the surface, hence the eruptions are typically of low explosivity – spatter eruptions and lava flows. In some cases, however, with more evolved magmas, where viscosity is slightly higher (e.g., trachy-basalt and trachyte; Kear and Wood, 1959), gas contents are retained more efficiently and more explosive eruptions result. These most explosive “dry” style of eruptions in Samoa generate large cones of scoria and more widespread ashfall hazards – a good example being the apparently young Tafua-Upolu. These events can be also relatively long lived – several years or more. Similar types of eruption are typical on Taveuni island in Fiji (Cronin and Neall, 2001). The following scenario (Table 5) is based on the famous historic eruption of the Paricutin volcano in Mexico, a volcano witnessed from birth onward as it grew from a farmers corn-field (Luhr and Simkin, 1993). In addition, subsidiary information comes from the geology of Samoa and other similar eruptions worldwide (e.g., Self et al., 1974).

Table 5: Summary of eruption scenario for an explosive scoria eruption.

Timeline	Events	Impacts/Hazards	Actions required
0-10 days	Earthquakes detected on seismographs – some felt by people nearby, one or two days before eruption.	Fear/unsettling of the population.	Identification of eruption zone. Public warning. Installation of volcanic monitoring network – seismic.
10-12 days	Eruption starts, with explosive blasts and initial ejection of soils and country rocks from the newly-formed vent area.	Volcanic bombs thrown out to 500 m radius. Possible pyroclastic surges moving laterally at >30 m/s out up to 500 m from the vent if eruption occurs in a wet area. Ashfall several cm thick in areas up to 3 km away.	Immediate evacuation of people in a 3-km radius of vent. Evaluation of wind direction and ashfall hazards. Public information updates. Regular aerial monitoring of eruption.
12-20 days	A scoria cone or chain of cones is rapidly formed by frequent ongoing explosive bursts. A 5-10 km high column of ash/lapilli is formed.	Volcanic bombs thrown out to 2 km radius Cone formed of up to c. 500 m diameter, burying all surroundings. Ashfall several cm thick in areas up to 10 km away – minor ashfall can occur at greater distances.	Expansion of evacuation zone to a 5 km radius and perhaps further in down-wind areas if ashfall is strong. Regular aerial monitoring of eruption. Monitoring of wind direction/strength to provide ashfall forecasts. Regular public information updates.
20 days – several years	Activity wanes and waxes as magma supply changes – there may be a transition to lava flow activity as later-erupted magma often has progressively lower gas-content as described in scenarios 4.4.1 and 4.4.2.	As above with varying areas affected depending on wind direction changes. Onset of spatter/lava activity coincides with cessation of significant ashfall. Lava-flow onset will begin to cover nearby areas.	Maintenance of evacuation areas. Regular aerial monitoring. Wind/weather monitoring. Regular public information updates. When eruptions have ceased for >6 months, wind down operations and evacuation restrictions.

4.4.5 Submarine flank collapses

A common feature of large oceanic islands such as Savai'i and Upolu is that they rise steeply from surrounding deep ocean floors. In addition, their slopes are made up of lavas and volcanic debris that in part cover unstable, mud-rich ocean sediments. Because of this situation, the stage is set for large-scale collapses from the steep flanks of the volcanoes, often from the submarine flanks (e.g. Keating et al., 2000). In several other similar volcanic chains, such as Hawai'i and the Canary Islands, such large-scale collapse events are known and are postulated to have formed major inter-regional tsunamis (e.g., Moore et al., 1989; Carracedo, 1996). Similar large-scale collapse features and the resulting debris-avalanche deposits have also been recognised on the submarine slopes of Savai'i and Upolu (Hill and Tiffin, 1993; Keating et al., 2000).

The prediction of such large events is currently impossible. The main hazard from submarine landslides is that of tsunami. Some authors have estimated run-ups of large Hawai'ian events as up to 300 m in the nearby areas (Moore et al. 1989). Certainly many coastal villages that are often <10 m above sea level would be destroyed. We currently have no idea of the frequency of such events in the Samoa area, and none have occurred from any of the world's oceanic islands in recent history.

5 INFORMATION REQUIREMENTS FOR VOLCANIC RISK MANAGEMENT

During evening discussions with field participants and a debriefing meeting at the Apia Observatory (MNREM) the following questions and needs were identified with respect to volcanic hazards assessment and emergency management in Samoa:

- i. Where will the next eruption be? The hazard map is too vague to specify areas where reduction activities could take place.
- ii. Where are the eruption threats in relation to population and infrastructure?
- iii. There is a lack of age data – in both determining the long-term evolution of the volcano, but also in quantifying past eruption rates and calculating probabilistic eruption functions.
- iv. What will happen when an eruption occurs? There is a lack of event scenarios for development of emergency response plans.
- v. There is a lack of data on historic and prehistoric eruptions, including traditional knowledge of events, consequences, responses and recovery.
- vi. There is a lack of understanding of the geological structure of volcanism in the area and specifically a lack of understanding of the structures present on the island. This hinders the development of an effective hazard map.
- vii. There is a lack of monitoring equipment and early warning systems for eruptions.
- viii. There is a lack of geochemical information, particularly aspects relating to the explosivity (magmatic gas content) of erupted magmas.
- ix. There is some degree of geological research ongoing in the area (US offshore cruises, US-based remote-sensing analysis, NZ-based volcanology analysis), but little coordination and in-country knowledge of this work.
- x. Upolu has been, up till now, ignored as a location for future volcanism, yet western Upolu appears as young as many parts of Savai'i, especially features such as Tafua Upolu.

6 RECOMMENDATIONS AND PRIORITIES FOR FUTURE WORK

The following recommendations (Table 6) derive from further discussions with the activity participants and are an attempt to identify reasonably achievable steps in improvement of the preparedness of Samoa for volcanic hazards. Most of the required information for an improved volcanic risk assessment relies on baseline geological/volcanological studies. Since funding for such baseline work is hard to secure, but they are urgently needed; we suggest cooperation with research entities within MSc or PhD projects. Some of them, like the dating of late Holocene volcanism deposits and collation and research of historical eruptions records, can be realised with very minor costs and a suitable Samoan MSc/PhD candidate. This will have a huge impact on our understanding of volcanic risks in Samoa.

Table 6: Recommendations for addressing needs in volcanic-hazard related emergency management in Samoa (note, all costs are given excluding professional time).

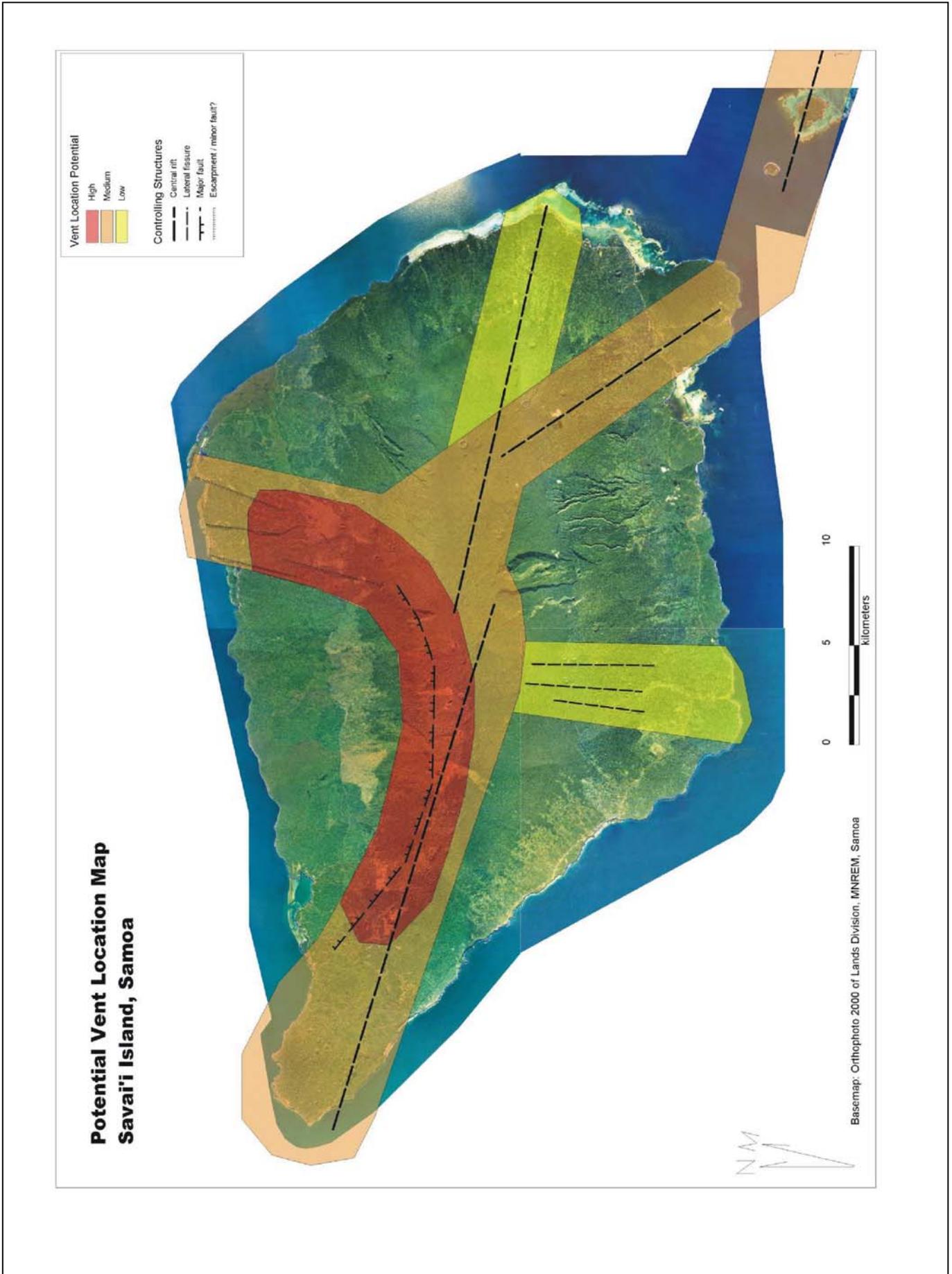
Need	Sub-tasks	Priority	Method	Est. Cost WST
Age data	Carbon-dating A – Littoral deposits and coastal tuff cones.	1	Targeted study of lava field coastal sites – sampling, X-ray diffraction and dating of coral or shell.	45 000
	Carbon-dating B – Cores from lakes and cones.	2	Traversing and coring of lake and swamp-filled craters, geochemical and physical analysis of ash and radiocarbon analysis of intervening sediment.	45 000
	K-Ar and Ar-Ar dating of older rocks.	3	Full sampling programme of all exposed lava flows on both islands with K-Ar and Ar-Ar analysis of matrix samples.	75 000
Historical information	Review of 1902 and 1905-1911 eruptions including time-lines, volcanology and consequences (English, and German sources).	1	Literature search, translation, review. Comparison to field exposures and modern volcanological analysis of similar types of eruptions.	5 000
	Traditional information held within legends, songs and dance.	1	Conducting workshops: (1) invitation of all elders from each island to workshops developing a disaster timeline. (2) Specifically-focused workshops in 3 locations (1 Upolu, 2 Savai'i) to gauge specific local traditional knowledge of disasters, community structure and past community responses to disaster. <i>(UNESCO – part funding.)</i>	45 000
Geochemical background	General petrology and geochemistry.	3	Full geochemical sampling programme and analysis using X-Ray Fluorescence, Laser-ICP-MS, Isotope analysis, Electron Microprobe analysis of phenocrysts and glass.	45 000
	Fluid-inclusion studies of eruption gas contents and rates of magma rise (= warning times).	3	Fourier Transform Infrared Spectrometry (FTIR) analysis of glass inclusions in Olivine, Pyroxene and Plagioclase, modelling of gas loss and ascension rates.	15 000
Ongoing geological work	Review of ongoing work in the area.	1	Contacting all known active research groups working on Samoa through collegial linkages using email. Cataloguing and maintaining records of work completed and requesting of publications. <i>(Observatory staff.)</i>	nil

Volcanology	Specifically-focussed studies on the volcanology of individual representative eruptions.	1	Detailed field investigations and sampling of Tafua Savai'i, Tafua Upolu, Apolima, Nuutele, spatter cones at Seuseu, Matavanu area, 1760 lava field.	15 000
	Analysis of the older volcanic sequence for evidence of submarine and sub-aerial signatures.	3	Field studies associated with sampling.	15 000
	Analysis of aerial photographs of cone structures, controlling faults and cone morphologies (size, slope, crater width, height etc).	1	Aerial photographic interpretation.	3 000
Structural Geology	Analysis of faults, rifts, internal island and regional structures, including tectonic driving forces.	1	Image-interpretation, field analysis of faults, literature review.	15 000
	Analysis of tectonic data including earthquake moments.	1	Historic data interpretation and installation of a temporary experimental seismic network.	15 000
	Analysis of inter-island and intra-island motion and stress regimes.	1	Installation of a permanent GPS network, including sites in each of the main hypothesised tectonic domains on each island.	150 000+
Monitoring and Early warning	Installation of monitoring equipment.	1	Installation and analysis (for baseline establishment) of permanent GPS and broad-band or low-frequency seismic stations.	>300 000
	Development of warning systems.	1	Construction of an alert level system including SOP's to set levels and recommended actions for communities and authorities to take at each level.	
Emergency management	Development of detailed scenarios for emergency management plans and tests.	1	Examination of past volcanologic record and historic eruptions of previous volcanoes.	3 000
	Development of national-level and community emergency plans.	1	National and community workshops to drive planning process, using participatory techniques, and testing and revision of plans through table-top exercises. (UNESCO – part assistance.)	60 000

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APPENDIX 1: POTENTIAL VENT LOCATIONS, SAVAI'I



APPENDIX 2: POTENTIAL VENT LOCATIONS, UPOLU

