VOLCANIC HAZARD AND RISK ASSESSMENT FOR TAVEUNI, FIJI ISLANDS

SOPAC Technical Report 298

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INTRODUCTION

Taveuni, the third largest island in the Fiji Group, is home to around 14 500 people (Ishri, 1997) who prosper from its young, fertile volcanic soils. Development is proceeding rapidly on the island due to its agricultural wealth and also the approach of the Millennium, Taveuni being located in a unique position astride the 180° Meridian. Taveuni is also the largest Quaternary volcano in Fiji, and its axial ridge is dotted with over 150 distinctive scoria cones, craters and fissure zones.

Aside from a brief consideration (Rodda and Woodhall, 1984), Taveuni has largely been ignored by those with a volcanic hazards interest. However, past archaeological, vegetation history, and soil studies have provided evidence of eruptions on the island within the last 2000 years (Frost, 1974; Southern, 1986; Shepherd and Neall, 1991). Recent geological study reveals that it last erupted sometime between 1460-1660 AD (Cronin, 1998; Cronin and Neall, 1998). This new geologic information reveals that Taveuni is an active volcano.

It is part of our responsibility as a society to prepare for events such as volcanic eruptions, and to develop plans to minimise human suffering and loss of life. This volcanic hazard and risk assessment is the first main stage in the hazard mitigation strategy for Taveuni volcano. This report outlines the results of the latest geological investigations on Taveuni, carried out from 1997 to 1999. The main objective of the study was to establish the volcanic eruption history of Taveuni, particularly the frequency, location and volcanic style of eruptions on the island. This geologic evidence can be used to assess the volcanic hazards present on Taveuni using the adage that “the past is the key to the future”. In this case we assume that, if there is no fundamental change in the geological setting of the volcano, its future behaviour will be similar in magnitude, nature and frequency to that it has exhibited in the past.

TAVEUNI - GEOLOGICAL SETTING

Taveuni is a large shield volcano complex (437 km^2), located at the northern end of the Koro Sea. Volcanism on Taveuni has occurred over the last approximately 780 000 years (Whelan et al., 1985). The volcanic activity followed a major change in the tectonic setting of Fiji, when around 3 million years ago active plate convergence ceased in the area and there was a general extension of the crust in the Koro Sea region (Colley and Hindle, 1984; Rodda and Kroenke, 1984). This extension of crust led to the development of several volcanoes surrounding the Koro Sea, including Seatura (on Vanua Levu), Koro, several other islands of the Lomaviti Group and finally Taveuni (Figure 1). It appears that many of these other volcanoes are now extinct, although Taveuni, the youngest, has erupted in the recent past. The current geological setting of Taveuni has been similar throughout its history, and this suggests that the volcano will be active for a long time into the future.

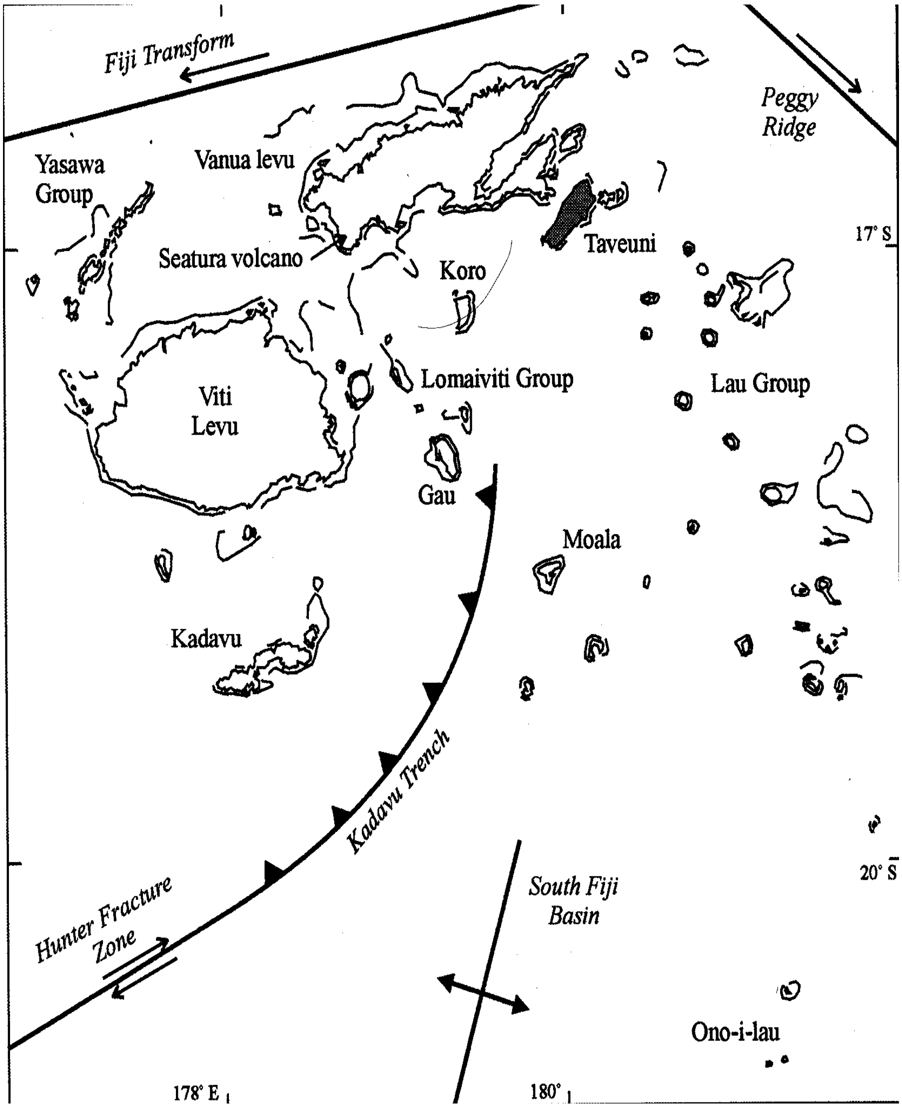


Figure 1: Generalised map of the main tectonic structural elements within the Fiji Group. Adapted from Colley and Hindle (1984), Rodda and Kroenke (1984) and Gill and Whelan (1989).

Taveuni is a basaltic eruption centre, and the island is dominantly constructed of lava flows with intercalated lava breccia and tephra deposits (Figure 2, in pocket). The island is strongly elongate in form and comprises a central ridge that rises to 1241 m above sea level. Construction of this high central ridge reflects the greatest volcanic productivity near the highest concentration of eruptive vents on the island.

The island's tectonic structure is strongly dominated by northeast-southwest faults (parallel to the ridge axis), all of which appear to be normal with dip-slip downward in a north-westerly direction (Figure 2). Graben-like features in parts of the central axis the island are also derived from blocks offset by parallel normal faults with NW down-thrown dip-slip motion. The main axis of the island probably represents the location of the deepest of the fault lines, which acts as a conduit for preferential upward flow of magma to the surface.

Will Taveuni Erupt Again?
THE VOLCANIC HISTORY OF TAVEUNI

This study has concentrated on the last 10 000 years of activity on Taveuni. Eruptive products were mapped and dated using a combination of radiocarbon dating, stratigraphic relationships and comparative deposit or landscape morphology. The chronology hinges on a framework of 31 radiocarbon dates that can be related to volcanic eruption products throughout the island (Appendix 1).

The results of this latest mapping and dating programme include a new map for the Holocene volcanic geology of Taveuni (Figure 2), and a history of 167 eruptive events since 9500 BC (Figure 3). This new chronology indicates an average interval between eruptions on Taveuni of c. 70 years. If we consider just the time since the known human occupation of Taveuni (370-110 BC; Wk6208), there were 36 eruptions, giving an average interval between eruptions of 60-65 years.

Using an average interval between eruptions on the island is however misleading. The recurrence of eruptions on Taveuni (Figure 3) is clearly intermittent, with distinct periods of relatively high-frequency activity. Eruptions occur less frequently between these highly active periods. Since 1200 BC around six high-frequency eruptive periods occurred, with intervals between them ranging from 200 to 400 years. Hence, intervals between eruptions on Taveuni are difficult to predict using simple mathematics. However, 60 years could be considered a low value (although not a minimum), while the maximum pause between eruptions we recognise since 1200 BC was 350-400 years.

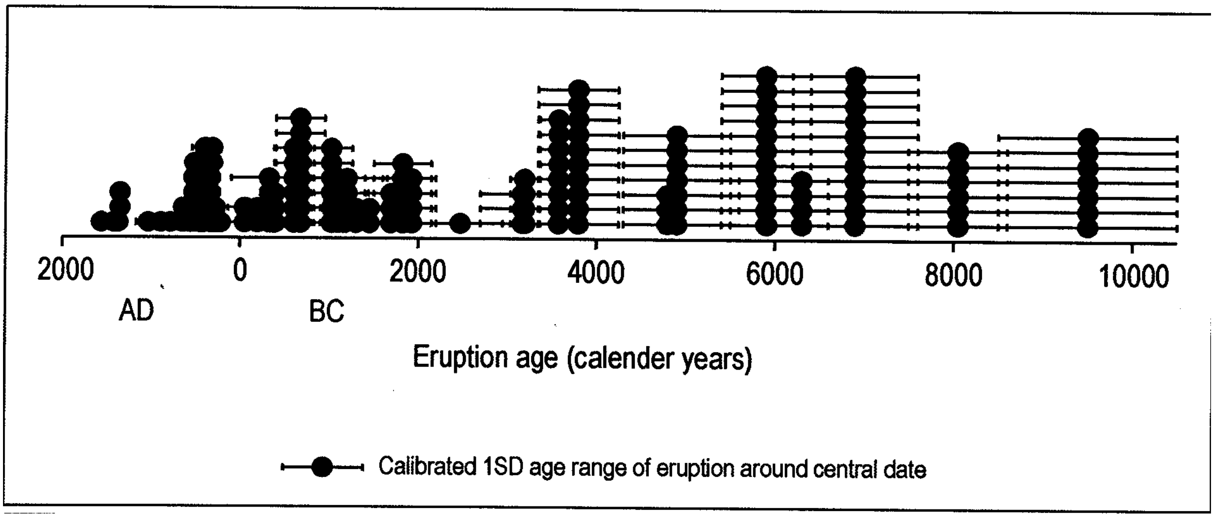


Figure 3: Ages of eruptions since 9500 BC on Taveuni. Eruption ages are in calendar years, based on calibrated radiocarbon dates collected and compiled during the geologic study of Cronin. For a list of dates and calibration details, see Appendix 1.

The latest eruption yet dated on Taveuni occurred sometime between 1460 and 1660 AD (Wk6209), in the South Cape area of Taveuni, whilst in central Taveuni the latest was some time after 1403-1443 AD (Wk6004). Given the continual nature of eruptive activity on Taveuni since 9500 BC, the known intervals between eruptions of between 60 and 400 years, and the latest activity only 340-540 years ago, it is almost certain that Taveuni is an active volcano. There is every chance that eruptive activity may re-commence in the near future on T aveuni, and the probability of activity within the next 100 years is high.

Where will the next eruption be?

LOCATION OF VOLCANISM ON TAVEUNI.

Taveuni is technically a “monogenetic” volcanic field, which is somewhat different from the classic image of a central-vent-type volcano (Blong, 1984). On Taveuni, for each new eruption, magma travels to the surface via a completely new pathway to create an eruptive vent where none were before. The magma travel pathways are influenced by weaknesses in the rocks, including past or active fault lines. Following the eruption, volcanism is never likely to recur at the exact same vent.

The nature of this monogenetic activity makes it difficult to predict the location of the next eruptive outbreaks on the island. We can, however, use the geologic structure of the island and the location of past vents to narrow down the location of future activity. Vents on Taveuni appear to be primarily located along the NE-trending fault systems, and they are particularly concentrated along the central axis of the island. In addition, all the youngest vents are located along the southern two-thirds of the island's axis, from the Lake Tagimaucea basin southward. The youngest vent north of Lake Tagimaucea is that of Narata, dated at older than 4690-4900 BC (Wk6731).

Using the above information and the spatial density of past eruptive vents, a first-order approach is to map zones of relative probability for outbreak of a new vent (Figure 4). The zone of greatest probability encompasses a thin strip centred on the central axis of the island, south of Lake Tagimaucea. A wider zone of moderate probability encompasses all sites of volcanism since 9500 BC.

What will happen when Taveuni erupts?
VOLCANIC PROCESSES AND MAGNITUDES ON TAVEUNI

Investigation of the deposits from past activity on Taveuni reveals that three main types of eruption occur: 1) non-explosive, lava-dominated, Hawaiian-style effusive eruptions; 2) mildly explosive, cone-building, Strombolian-style eruptions, producing moderate-sized tephra (volcanic ash) falls and small-volume lavas; and 3) explosive, hydrovolcanic (magma-water interaction) eruptions, producing low cones of ejected rock debris around the cone. The first two types of eruption are by far the most common. Individual past eruptions on Taveuni each directly affected areas of between 2-10% of the total island area.

1) Lava-dominated eruptions

These types of eruption are well known from the Hawaiian volcanoes, and although they are non-explosive, lavas produced can inundate large areas. These eruptions are derived from long fissure zones, some of which may be a kilometre or more in length. At the vent fissure a fire-fountain of scoria and highly fluid magma is erupted several hundred metres high. This builds up small scoria and agglomerate cones around the vents. Associated with the fire-fountaining is a continual discharge of highly-fluid magma causing lava flows. Many of the lava eruptions on Taveuni developed from a series of aligned fissures, and this may cause simultaneous lava flows in several different areas that may be several kilometres apart.

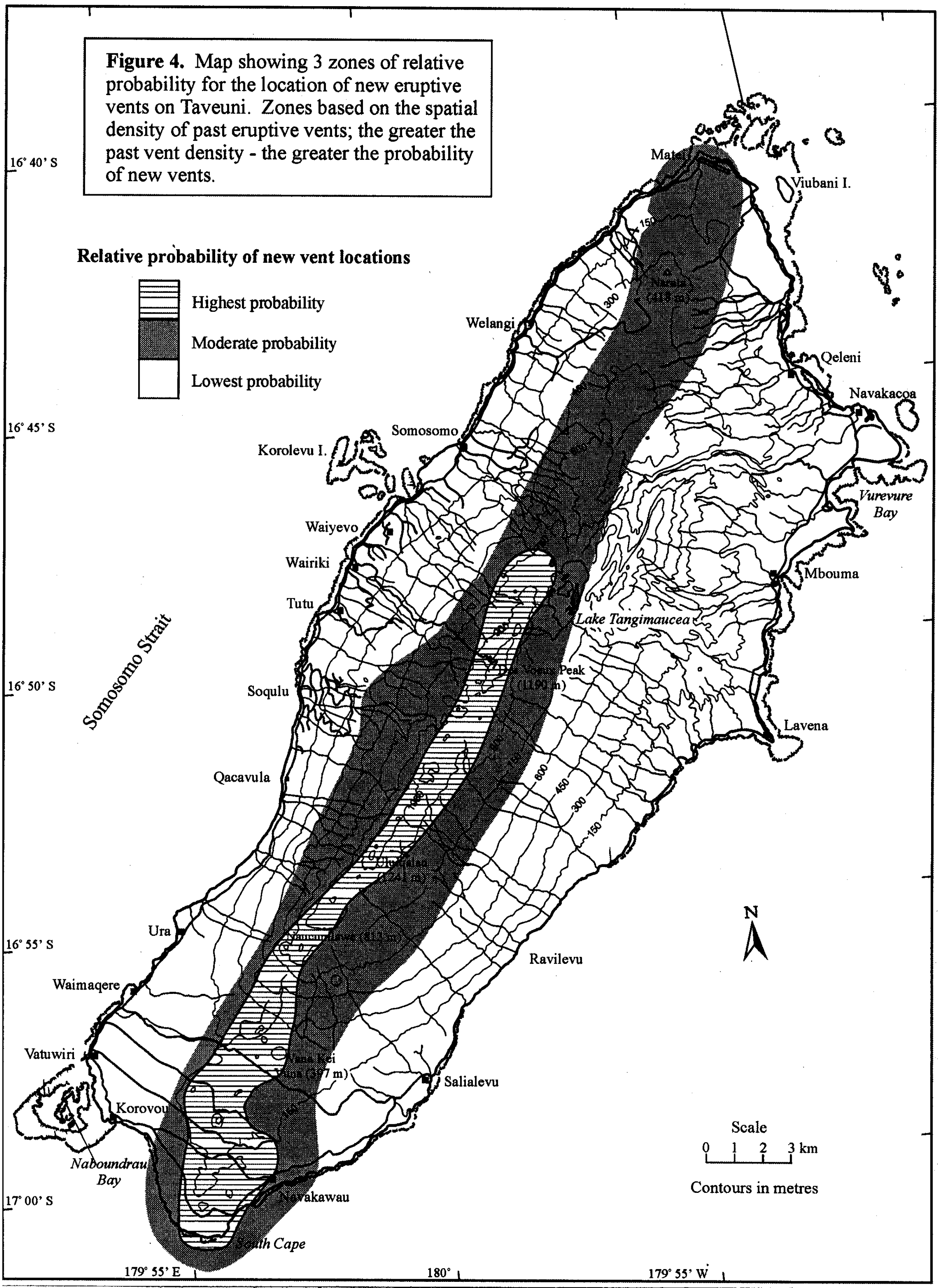


Figure 4. Map showing 3 zones of relative probability for the location of new eruptive vents on Taveuni. Zones based on the spatial density of past eruptive vents; the greater the past vent density - the greater the probability of new vents.

The Taveuni lavas often flowed to the sea down the steep flanks of the island, covering distances up to 8 km. Individual flows ranged between 20 m wide for highly fluid flows on steep slopes, and up to 5 km wide for very large Hawaiian-type flows on broad flat areas (particularly in south Taveuni). Highly mobile, low-viscosity pahoehoe-type lava flows occurred, forming and flowing within tubes and channels. In addition, more slowly moving, clinkery/blocky aa-type lavas also occurred. Normally several lava flows were extruded with each eruption. The earlier-extruded lavas from each eruption flowed down and infilled the main drainage channels. Later flows diverged from the initial flow paths to inundate new areas.

Holocene lava flows from typical eruptions on the steep central portions of the island covered areas between 3 and 7 km^2, being mostly valley confined. Lavas on flatter areas at the north and south of Taveuni usually covered much larger areas, between 11 and 24 km^2. Lava flow volumes ranged from 0.01 to 0.25 km^3 or 10 to 250 million m^3, the largest flows resulting from Hawaiian-style eruptions. These eruptions may continue for months to years; a good comparative example is the 1905-1911 eruption of Savai'i in Samoa (Kear and Wood, 1959).

2) Cone-building eruptions

These eruptions are more explosive due to a greater amount of gas within the erupting magma. They may form along an elongate fissure or from a central vent. Such eruptions on Taveuni produced hot columns of rising volcanic ash and gas that rose several kilometres above the vent. Tephra (the technical name for "volcanic ash") and gases were directed by the wind, with heaviest ash falls occurring in downwind areas (Figure 2 inset). Scoria cones, up to 250 m high, may be constructed around the vent area. Lava flows are also generated during these eruptions but tend to be confined to total areas of between 1 and 10 km^2.

These eruptions, known as Strombolian style (after the famous Italian volcano Stromboli; Blong, 1984), produced widespread tephra falls that are preserved in the geologic record of Taveuni. Field data of 10 tephra layers on Taveuni were used to construct isopleth maps (maps of the distribution of the largest clasts within tephras) for assessing eruption parameters, and isopach maps (maps of tephra thickness) to calculate volumes of eruptions. Tephra volumes ranged between 6 and 16 million m^3, and typical eruptions covered areas between 6 to 17 km^2 with more than 10 cm of scoriaceous tephra (Fig. 2 inset maps). Wind dispersal of most tephra is normally towards the populated western half of the island, driven by the prevailing low-level trade winds from the south-east (e.g. Benubenu tephra, Figure 2 inset). Tephra erupted to higher levels (>6 km) is affected by a prevailing westerly air flow, and hence light tephra falls are probably deposited on the eastern flanks of the island and further afield. Using the Taveuni isopleth data and plotting them on the diagrams of Carey and Sparks (1986), it appears that the tops of many past Taveuni eruption columns were probably between 6 and 11 km high. Many tephras were erupted from more than one vent, e.g. the Tavuyaga tephra (Figure 2 inset) comprises the products from three separate vent locations, erupting within a short space of time (<1-2 years?).

These eruptions on Taveuni may last from months to years, with tephra falls from longer eruptions spread across different areas as wind directions change. A good comparative eruption of this type was that of Paricutín, in central Mexico, from 1943 to 1952 (Luhr and Simkin, 1993).

3) Hydrovolcanic eruptions

These eruptions occur where rising magma encounters water, whether swamps, lakes or shallow sea water. Magma at up to 1100ºC causes super-heating of water it meets, and an explosive chain reaction occurs. These eruptions generate radial blasts of water, gas and rock particles (pyroclastic surges) which move at extremely high velocities (55-100 km/hr) up to 6 km from the vent location (e.g. Moore, 1967). Repeated blasts of this type build up a ring of deposits surrounding the vent. Hydrovolcanic eruptions are less common on Taveuni than the “dry” tephra- and lava-producing eruptions. They occurred from shallow marine vents, some that were directly on the coast of Taveuni and others within lagoons further offshore. Some craters in the central highlands of the island may also have been formed by hydrovolcanic eruptions, where magma encountered standing water, swamps or saturated sediments.

On Taveuni, pyroclastic surges from these eruptions deposited ejecta containing clasts up to 5 cm in diameter, up to at least 1 km from the vent. Beyond 1 km the deposits are poorly preserved. Pyroclastic surges in similar types of eruption elsewhere in the world travelled between 2 km and 6 km from the vent (e.g. Moore et al., 1966; Moore, 1967; Self et al., 1980). Judging from the preserved deposits on Taveuni, pyroclastic surges probably did not travel beyond 3 km from the vent. Hydrovolcanic eruptions also generate fine-grained tephra columns which distribute tephra long distances from source (e.g. Self et al., 1980).

A hydrovolcanic phase of activity preceded some of the lava-dominated or cone-building eruptions on Taveuni, where magma rose through wet sediments and soils. Once the initial blasts were over, the eruptions reverted to either of the other two styles.

4) Other volcanic phenomena on Taveuni

Eruptions that produce large amounts of volcanic ash may also lead to the formation of volcanic mudflows (lahars) and sediment-rich floods. Heavy rains during and following eruptions trigger such events. Some eruptions on Taveuni were accompanied by lahars. This is understandable when it is considered that rainfall exceeds 6 m per annum in the central portions of the island, and often falls in high-intensity downpours (Krishna, 1980). On the steeper and more-dissected slopes of Taveuni, lahars were mostly confined to one or two catchments, with narrow (<50 m) flow paths. However, on broader, flatter areas, mostly in coastal regions, lahars spread laterally in places; one flow spread out to at least 500 m wide in the Ura area of Taveuni. These events may occur for up to 1-2 years after an eruption.

Volcanic tsunamis on Taveuni may be generated by offshore water-magma eruptions. In addition, tsunamis may also be generated by large collapses or landslides on the steep subaerial or submarine flanks of the island. At least two subaerial collapse features may indicate past sites of tsunami generation during the late Holocene. Others may be hidden below the sea. Such events may also be unrelated to volcanism, and instead be triggered by earthquake events. The layered nature of Taveuni rocks, with hard lavas intercalated with softer, porous volcanic deposits and sediments, predisposes this area to block-slide failures.

During many of the Taveuni eruptions large quantities of volcanic gases were probably released; these would have mostly comprised CO_2, SO_2, H_2S, HCl, and HF. Gases are affected by the wind, and upon interaction with moist air form acidic aerosols (tiny droplets of acid in the air); aerosols of dominantly sulphuric acid probably also formed where lavas entered the sea.

Other events that probably occurred during Taveuni eruptions include lightning (associated with tephra fall), hot block-and-ash flows (associated with aa lavas collapsing on steep slopes), fires, and volcanic earthquakes.

What heralds Taveuni eruptions?
PRECURSORY SIGNALS OF ACTIVITY.

Events that may occur before an eruption include seismic activity, ground deformation, hydrothermal phenomena, and gas and water chemical changes. Of these the most probable that will be initially noticed on Taveuni is seismic activity. The other effects may be noticed as the eruption commencement draws near. Volcanic earthquakes are generated as rising magma forces its way through bedrock by creating and filling cracks within it (e.g. Yokoyama and de la Cruz-Reyna, 1990). The rising magma exerts intense pressure on the overlying and surrounding rock.

On Taveuni the erupted rock type and relatively small volumes of eruptions indicate that they are probably preceded by only a very short warning period. The best example of the warning of a similar monogenetic volcanic field eruption was that of Paricutín, in Mexico, 1943 (Yokoyama and de la Cruz-Reyna, 1990). In this case, earthquakes were instrumentally detected 45 days before the eruption, although these had only become large enough for people to notice by two weeks before the event began. In the region of the vent, cracks in the ground and steam venting began less than 5 hours before magma reached the surface. The Paricutín eruption involved around 10 times the magma volume of most Taveuni eruptions, and hence a shorter warning period is anticipated for future Taveuni eruptions.

HAZARDS OF TAVEUNI ERUPTIONS

The accompanying volcanic hazard map (Figure 5) is based on an interpretation of the geological data for past Taveuni eruption locations, magnitude and volcanic styles. Two sets of hazard zones are mapped; the first for ground- or near-ground-based hazards (e.g. lava flows, near-vent explosions and gases, hydrovolcanic eruptions, ballistic impacts and lahars), and the second for tephra (volcanic ash) fall hazards.

1) Lava flows

Lava flows are likely to cause the greatest damage from future eruptions on Taveuni; they burn and destroy everything in their paths. They are very hot; those on Taveuni are likely to be between 940-1125 °C (Macdonald, 1972). They can also generate potentially widespread fires from their margins. The potential for fires is great due to the heavily forested nature of Taveuni. The velocity of lava flows on Taveuni depends on the style of flow (fluid pahoehoe vs. clinkery aa flows) and the slope that they are emplaced on. On the typically steep slopes of Taveuni, the flows could travel between 1 and 9 km/hr. Hence this implies that many Taveuni lava flows could reach populated areas and the coast within a only a few hours of onset of the eruption. Fires preceding lava flows may reduce the time available for evacuation even further. Lava-flow effects are long term, and include destruction of all structures in their paths, blockage of roads, burial of productive land and inundation of reef systems.

Small secondary explosions may also occur from some lava flows if they travel over areas of ponded water or saturated ground, or when they enter the sea. These explosions may shower an area within a few hundred metres of the flow with rock debris. Many Taveuni lavas have flowed into the sea, and this is a highly probable occurrence in future eruptions.

Clinkery aa-type lava flows emplaced onto steep slopes on Taveuni have generated block-and-ash flows, presumably by collapsing of the rubbly lava flow fronts. The block-and-ash flows were hot and rapidly descended the slopes ahead of the lava, with repeated small collapses building up 10-20 m of deposits. The high velocities of these block-and-ash flows compared to the relatively slower-moving lavas increases the hazards in the downslope areas of the aa lava flows, and these block-and-ash flows may affect larger areas than the lava flows that generated them.

Lava flow paths are controlled by the topography. The earliest flows tend to follow existing drainage paths (stream and river valleys), but once these are filled by lava, later flows are able to divert into alternative flow paths. The hazard map of Taveuni (Figure 5) shows that the highest risk of lava flows is along the main drainage channels of the most recently active southern portion of the central ridge. A moderate level of lava-flow hazard lies outside the main channels along the southern flanks of the island, and within the main channels on the flanks of the less-active northern portion of the island's central ridge (yellow areas, Figure 5).

The greatest hazards related to lava fire-fountaining and the opening of lava vents and fissures are mostly restricted to the axial portions of hazard zone A, along the southern central ridge of Taveuni (Figure 5). Lower degrees of these vent-related hazards are mapped within hazard zone B along the northern end of the ridge, and in a collar zone surrounding the axial portion of hazard zone A along the southern extent of the ridge.

2) Near-vent explosions and ballistic ejecta

The onset of Taveuni eruptions involves the opening of a crack in the ground and subsequent explosive widening of this and creation of an eruptive vent or fissure. Vent-clearing explosions, sometimes exacerbated by interaction of hot magma with wet soils and sediments, shower the surrounding few hundred metres with rock debris. Later, when the vent is established, individual explosions eject very large clasts into the air that travel on ballistic pathways (little affected by wind or the vertical thrust of gas from the crater). These large particles can be >1 m in diameter and rain down mostly within a 1-km radius of the vent (e.g. Paricutín; Trask, 1943). On Taveuni, ballistic blocks up to 140 cm diameter were ejected 1.8 km from the vent during the Benubenu tephra eruptions (Figure 2 inset).

Ballistic impacts and near-vent explosions will destroy any nearby structures, and vegetation, both from physical impact and, in the case of hot ballistics, fire. The greatest hazard from these events is within Zone A, along the southern portion of Taveuni's central axis. Moderate hazard exists along the northern portion of the central axis and within a collar region surrounding Zone A along the southern axis of the island (i.e. parts of the yellow Zone B on Figure 5).

3) Volcanic gases

Volcanic gases are mostly (in order of decreasing abundance) H_2O, CO_2, SO_2, HCl, NH_3, H_2S, HF and a few other minor constituents (e.g. Macdonald, 1972). Their main hazards include respiration problems in humans and animals, acidic burning and toxicity to plants and animals, and corrosiveness to metal structures and equipment. The effects of the gases depend on their concentration, and they are rapidly diluted with increasing distance from the vent. Hence the greatest hazard from volcanic gases is expected to be within a few kilometres of the vent, although minor effects could be experienced in areas further downwind. Volcanic gases rapidly form aerosols in moist air and can also generate acid rains or fogs; these may have (mostly minor) effects at longer distances from source. Volcanic gases (commonly H_2SO_4) are often also generated when lava flows into the sea, e.g. during the 1905-1911 Savai'i eruptions (Anderson, 1910).

The greatest hazard from volcanic gases is mapped within the axial portions of zone A (Figure 5). Moderate hazard exists within the axial portions of zone B, and a lesser degree of hazard from acid rains or fogs occurs within the tephra hazard zone 2.

4) Lahars

Lahars are rapidly flowing mixtures of rock debris and water, flowing from the flanks of volcanoes (Smith and Fritz, 1989). On Taveuni they are most likely to be generated by rainfall remobilisation of recently emplaced tephra deposits on the steep flanks of the island. They can also be generated on Taveuni by collapse of parts of the island's flanks. Lahars sweep away or inundate everything in their paths. Common effects include, destruction and burial of buildings, roads and bridges, as well as burial of crops and long-term damage to plantation land. In addition, because of their velocities that can commonly exceed 30 km/hr (Cronin *et al*., 1997) there is little warning of their arrival, and little chance to escape them.

Lahar paths are strongly controlled by existing topography. The greatest hazard for lahars is mapped within zone A along the main channels radiating from the southern portion of Taveuni's central ridge. A moderate degree of hazard from lahars is mapped within zone B, along the main channels of the northern part of the ridge, and in other areas of the island's flanks along the southern part of the ridge (Figure 5).

5) Hydrovolcanic explosions

The main agency of hazard from hydrovolcanic explosions is repeated radial blasts of gases, water and rock debris, known as pyroclastic surges. These surges travel at velocities of 50-300 km/hr and all life is normally wiped out within their range, by impact and abrasion of solid clasts (some up to tens of cm across) and the blast shock wave (e.g. Taal in 1965; Moore *et al*., 1966). However, the range of devastation from pyroclastic surges on Taveuni is expected to be limited to within 2 km of the vent, based on past deposits of these events. Eruptions of this type in other areas have affected areas up to 6 km from the vent (e.g. Moore, 1967). Structures, vegetation and crops within range of the surges are also destroyed or buried. These eruptions generally form a cone of ejecta around the vent (a tuff cone) with a basal area of up to c. 0.25 km^2. Due to their extremely high velocities, pyroclastic surges are almost impossible to escape within their range.

The main requirement for generating a hydrovolcanic eruption is a body of water in the path of magma ascent. Hence the greatest hazard area for the effects of such an eruption on Taveuni is mapped within zone A (Figure 5), both offshore at the southern central coast of Taveuni and at locations of swamps or lakes along the southern portion of the axial ridge. Areas within zone B, both along the northern portion of the ridge and in areas flanking the southern ridge segment, are at a moderate risk from the effects of hydrovolcanic explosions. Hydrovolcanic eruptions may also generate tephra falls, although these are normally of fairly small volume. The hazards of hydrovolcanic-generated tephra falls are greatest within tephra hazard zone 1 (Figure 5) and are subject to the same distribution effects as other tephra falls as discussed below.

6) Tephra falls

Tephra (volcanic ash) falls are the second-most common volcanic hazard (after lava flows) likely on Taveuni. The scale of Taveuni tephra eruptions, although small from a global perspective, could cause considerable local damage on the island, due to the location of people within close proximity to eruptive vents.

Hazards from tephra falls include collapse of house and building roofs under tephra thicknesses of >10 cm, this being the most common cause of fatalities from ash falls (Blong, 1984). If people are in the open, tephra particles (which may still be hot in some cases) of >20 mm in diameter may cause severe injuries. Additional hazards from tephra fall include generation of fires, which occurred during past Taveuni eruptions of >30-cm thickness of tephra (containing hot clasts of >4 cm diameter) onto forest vegetation. Fires may also be started by lightning which is commonly associated with tephra plumes. Heavy tephra falls (>10 cm) may cause considerable damage to crops grown in the area. Plant leaves are likely to be burnt and removed by falling tephra particles. In addition, buried areas may need to be cleared of tephra to enable replanting. Even thin falls of tephra (1-5 cm) may contaminate food crops and water supplies, corrode metal structures and equipment, and affect the operation of outside machinery (e.g. generators) and vehicles. Fine-grained tephra may also cause respiratory problems in people and animals in fallout areas.

The isopach maps of Taveuni tephras (Figure 2 inset) indicate that falls of >20 cm thick can occur up to 4-5 km from the source vent. Isopleth data (maps of largest particles within tephra deposits) indicate that particles >20 mm in diameter may fall up to 2-3.5 km from a vent, and particles >40 mm up to 1-2 km. Eruption columns that reach 6-11 km high may also pose considerable hazard to passing air traffic, especially if tephra clouds are widely dispersed by wind (Johnson, 1988).

Tephra fall direction and distance of dispersal are controlled by the wind direction and velocity at the time of eruption. Upper-level wind data from the nearest measurement site, Nadi (Ried and Penny, 1982), indicate that at lower altitudes (0-3 km) the predominant flow is easterly or south-easterly, whilst at higher levels (e.g. 6 km) the predominant air flow is westerly. This implies that Taveuni tephra falls will be mostly dispersed to the west or northwest from the lower levels of eruption columns, whilst tephra ejected to higher levels will be distributed mostly to the east (Figure 5 inset wind rose diagram). The Taveuni-style eruption columns, although as high as 11 km, probably contain most material within their lowest few kilometres (similar to some Hawaiian eruptions, e.g. Parfitt and Wilson, 1999). Hence, the thickest tephra falls are most likely to be dispersed in a W-NW direction, with the most distal fine-grained falls occurring most commonly to the east. Typical wind velocities are highest at the Nadi site (Ried and Penny, 1982) during the dry season (May-October), particularly at higher altitudes (1.5× wet-season velocities at 6 km). This implies that a dry-season-erupted tephra may be dispersed significantly further than if it were erupted during the wet-season.

Tephra hazards are mapped in two main zones. The greatest tephra hazard is mapped within tephra hazard zone 1 (Figure 5), which represents the area that is subject to falls of >20 cm from an eruption within the most-active southern portion of the Taveuni axial ridge (zone A). A moderate tephra hazard is present within tephra hazard zone 2, which represents the area subject to falls of >10 cm from eruptions along the southern ridge portion (zone A), OR, >20 cm from an eruption from the zone B areas (northern portion of the Taveuni ridge and areas flanking the central southern ridge portion). It should be strongly stressed, however, that only a small portion of each of these zones will ever be affected during any single eruption. The portion affected will depend on the location of the eruption, its magnitude and the prevailing wind direction and speed. The area covered by one past eruption is indicated (Figure 5 inset map) is given as an example.

7) Volcanic earthquakes and ground rupturing

Earthquakes associated with the ascent and eruption of magma are common with most volcanic eruptions, and the Taveuni events are likely to be no exception. The monogenetic nature of these eruptions may in fact result in greater seismic energy release than an eruption at a reawakening central-vent-type volcano (e.g. Yokoyama and de la Cruz-Reyna, 1990). Individual earthquake magnitudes are likely to be relatively small (Magnitude <4.0), although these may damage buildings and structures in some areas. Ground rupturing associated with volcanic earthquakes is normally limited to near-vent areas, which are likely to be along the main central axis of the island. Hence the hazard zones for volcanic earthquakes and associated ground rupturing are likely to be the same as those mapped for other near-vent hazards, such as explosions and ballistics (Figure 5).

8) Volcanic tsunami

Volcanic tsunamis are likely to be generated on Taveuni from either offshore hydrovolcanic explosions or from collapses of the edifice flanks (subaerial or submarine). Hydrovolcanic explosions on the scale of the Taveuni eruptions will probably not generate large tsunami events, and any waves generated will probably be localised to the areas otherwise directly affected by the eruption products. Flank collapses remain as the most likely cause of volcanic tsunamis from Taveuni, volcanic in some cases only due to the fact that the collapses are from a volcano's flank, because they may not be generated by eruptive activity. Such tsunamis generated by collapse events are recorded from Japanese volcanoes, (e.g. Unzen, 1792), while those generated by avalanching of lava into the sea are reported from Matavanu (1906) in Savai'i (Latter, 1981).

The geologic composition of Taveuni is inherently unstable. The island is made up of steeply dipping layers of hard lava flows, intercalated with weak layers of loose breccia and tephra deposits. Block slides from the island's flanks can be generated by a build-up of hydrostatic pressure leading to subsequent gravitational failure. Triggering for the failure may be a tectonic earthquake, seismicity associated with an eruption or seismicity from a magma intrusion event. Large-scale collapse features are commonly recognised on the Canary Islands, which are very similar in construction to Taveuni (Carrracedo, 1994). Small (c. 0.5 km^2) possible block-slide collapse features are recognised in parts of the coastline area of Taveuni; these may have generated tsunamis, however tsunami deposits have not been identified on the island.

Hazards from volcanic tsunamis are not mapped on Figure 5. Areas likely to be affected can be any area of the coastline of Taveuni and coastlines of neighbouring islands that face Taveuni, i.e. Vanua Levu, Rabi, Kioa, Qamea, and Matagi. Extreme events may impact as far afield as Vanua Balavu, Koro and Viti Levu. As with all tsunamis the effects on coastlines are dependent on the bathymetry, as well as the slope of the coastal land area. Low-lying coastal flat areas are generally at greatest risk.

Who and what is at risk?

ELEMENTS AT RISK FROM FUTURE VOLCANIC ACTIVITY OF TAVEUNI

1) Population

The c. 14 500 inhabitants of Taveuni (Ishri, 1998) are the most important element at risk from volcanic activity on the island.

The main population centres are located along the western flanks of the island; 81% of the population are in the southern and western portions of the island (10 243 people in 1997; Ishri, 1998). Areas of rapid population growth on Taveuni over the last ten years include Matei, Qila, Somosomo/Naqara and Delai Vuna (Figure 6). In addition there is smaller-scale population growth all along the SW and S coastal areas of Taveuni. Population growth appears to be related to the locations of freehold land which is being split from large estates into small blocks in the Delai Vuna and Naqara areas.

An important redistribution of population on Taveuni during daytime is to schools. There are more than 4000 school children in Taveuni. Important schools along the western and southern parts of the island are in or near Somosomo/Naqara, Wairiki, Vatuwiri, Vuna/Korovou, Navakawau and Salialevu (Figure 6). The former two locations host the highest student numbers.

The hazard map (Figure 5) indicates that villages along the west coast from Somosomo southward, plus those at the southern end of the island, have the greatest potential hazard from substantial (>20 cm) tephra falls. Villages with the greatest potential hazard from lava, lahar and block-and-ash flows include parts of Somosomo/Naqara, Qarawalu and Salialevu, whilst many others in the southern half of Taveuni are located near the hazard zone A areas. In addition, many isolated houses or groups of houses in the southern half of the island lie within the hazard zone A, especially in the central area south of Qarawalu, where additional hazards include near-vent explosions, ballistics, and hydrvolcanic explosions along the coast. Villages with a moderate hazard from the flowage hazards include almost all of the southern-half villages (south of Somosomo), with the possible addition of Welagi and Qeleni villages in the northern half of the island.

The population should be relatively resilient in the face of most volcanic hazards on Taveuni. Lava flows should be easily escaped on foot. Associated fires may be more difficult to escape, but could certainly be avoided or halted by constructing fire-breaks. Most tephra falls should be survivable, particularly if shelter is found and tephra is regularly removed from its roof. The narrow dispersal of many Taveuni tephra falls should also allow rapid escape from heavily affected areas. The most vulnerable people on Taveuni are those living in areas where new eruptive vents may open, particularly if the eruption is hydrovolcanic or begins with hydrovolcanic activity. This includes all people living within the boundaries of the central portion of hazard zone A.

2) Medical facilities

Current medical facilities on the island include a 42-bed hospital at Waiyevo, capable of curative care, maternity, rehabilitation, outpatient and accident/emergency services. A new hospital development is planned near the site of the present hospital at Waiyevo. Additional to this are two nursing stations sited at Vuna/Korovou and Bouma villages (Figure 6). Medical staff presently comprise four medical officers, 4 sisters and 8-9 staff nurses (Ishri, 1998).

The Waiyevo hospital and the Korovou nursing station are within the tephra hazard zone 1 and are potentially subject to tephra falls of >20 cm, whilst the Bouma station is subject to a lower degree of tephra fall hazard and may receive falls of >10 cm. The Waiyevo hospital and Korovou station are both also located within a zone of moderate hazard (zone B) from lava, lahar and block-and-ash flow events.

The existing Waiyevo hospital buildings are of relatively high construction standard - although they are nearing the end of their useful lifetime and are to be replaced by the new hospital development.

Like any other buildings, a direct impact of any of the flowage hazards would cause almost complete destruction. However, the most likely hazard these hospital and nursing stations may face is that of tephra fall, and possibly also acid rain and fire. With heavy falls of tephra (>10 cm), hospital buildings are highly vulnerable to roof-collapse, which is exacerbated if tephra falls wet. Tephra falls may cause short-circuiting and air-intake blockage to the diesel electricity used employed at the hospital. Fine-grained tephra may cause respiratory problems in staff and hospital patients during and following falls. Tephra falls and acid rains may also cause accelerated corrosion and premature deterioration of buildings.

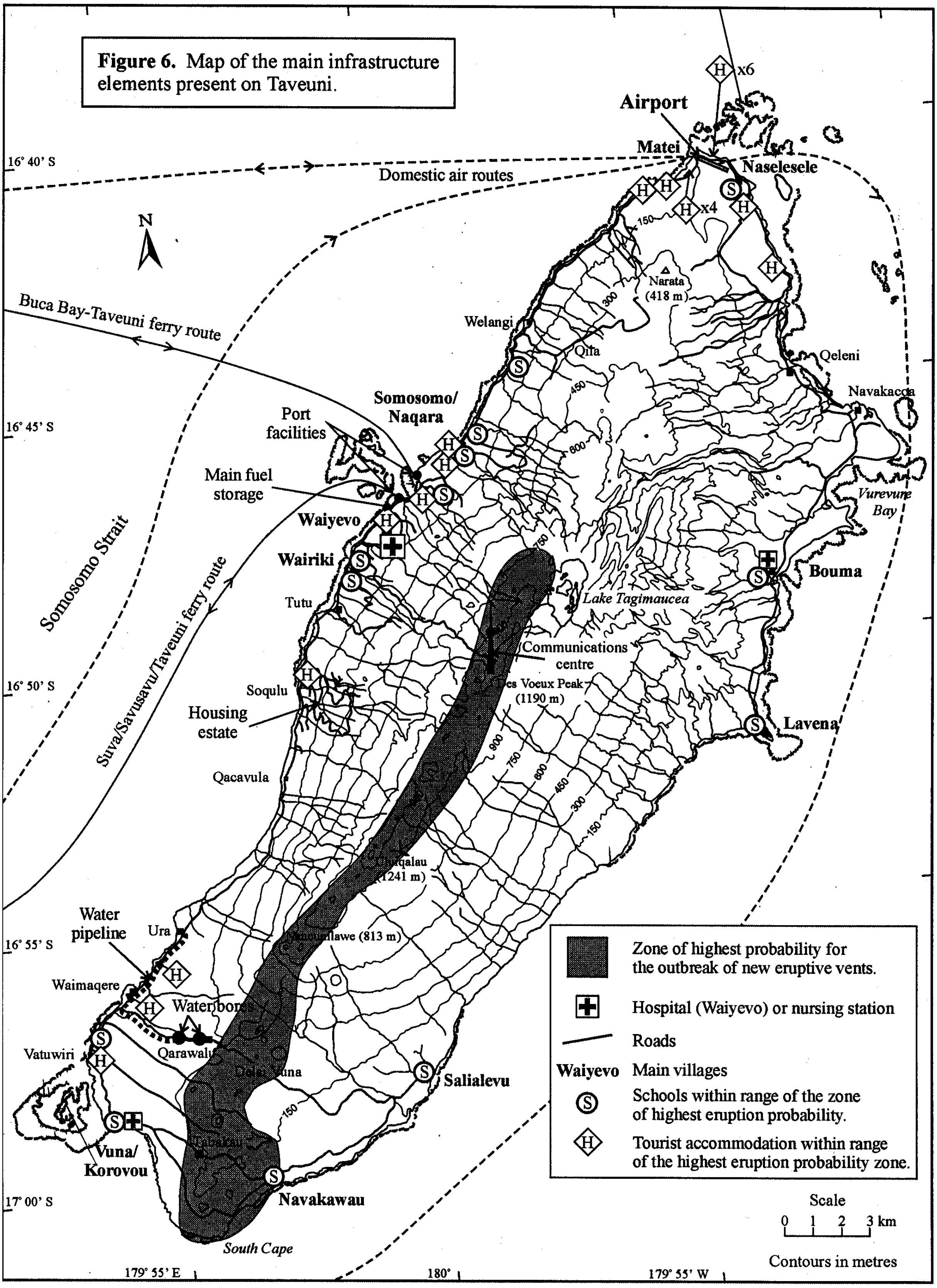


Figure 6. Map of the main infrastructure elements present on Taveuni.

In the event of an eruption near Waiyevo, the island may effectively be without local medical facilities sufficient to cope with casualties from the events.

3) Buildings/homes and shelter

The main concentrations of buildings on Taveuni are generally those associated with villages. Exceptions to this include tourist resorts, hotels and foreign-national's holiday houses which are often located outside the main village areas (Figure 6). The greatest capital investments in dwellings and hotels are probably in the Matei area, where international visitors are constructing large numbers of private holiday homes. Other important building areas include Qila and Delai Vuna, where many new private houses are currently under construction by local residents. The other important buildings are those of schools, with large secondary schools near Welagi, Naqara, and Wairiki, as well as smaller primary schools in most of the main villages.

Hence, the main concentrations of buildings at risk from flowage hazards are those in parts of Somosomo/ Naqara, Salialevu, and Soqulu, within parts of zone A (Figure 5). Other buildings and homes subject to moderate flowage hazards include all those within hazard zone B - effectively most of the inhabited areas in the southern half of the island. Almost all areas south of Somosomo are subject to the high risk from tephra falls of >20 cm thickness, whilst almost the entire island area could possibly be affected by lesser falls. Buildings and homes subject to the greatest hazard from near-vent explosions, ballistics and hydrovolcanic events are those within the central portion of south Taveuni (south of Qarawalu) within the axial portion of hazard zone A (Figure 5). This includes the developing building areas of Delai Vuna, Qarawalu, Tabakau and the south coast areas.

Buildings, no matter how well constructed, will not withstand lava flows or lahars; most will also not withstand pyroclastic surges. Many existing and new buildings on Taveuni, particularly those of Fijians, have a flat or low-sloping roof design. This type of construction gives rise to greater susceptibility to building collapse under heavy ash falls. Steeper-pitched roofs have been shown to have a far greater resistance to damage by ash falls in many overseas examples (Blong, 1984). Well-sealed buildings are also rare on the island (due to design for cyclone resistance). However, well-sealed buildings afford the best protection for people that are susceptible to respiratory problems under ash falls.

4) Electricity supplies

Each of the eight major villages on Taveuni has a rural electricity scheme that is maintained individually. These schemes normally involve diesel or wood-fuelled generators with a wiring system to the main village buildings and most houses. Other villages, estates and more widely separated houses have individual generators, or small hydroelectric schemes (Tutu) and solar power systems.

Individual village and house generator systems are vulnerable to the same volcanic hazards as buildings in these areas. Hazards that the electricity systems may be specifically vulnerable to include tephra fall and lightning. Almost the entire island is subject to some degree of tephra fall hazard, although only a small area will be affected at any one time. Tephra may cause air-intake blockage and severe abrasion damage to generator engines. Volcanic ash is also highly conductive and will likely cause short-circuiting and power outages in any intra-village power system, as well as in individual generators, if they are not well protected. Lightning associated with tephra clouds may also cause short-circuiting within village electricity systems. Hydro-electricity schemes are vulnerable to abrasion by ash if it is taken with water into turbine systems - a large-scale example of this occurred in the 1995-96 eruptions of Ruapehu volcano in New Zealand (Malcolm and van Rossen, 1997).

5) Water supply and reticulation

Most of the main villages on Taveuni have a local water supply and reticulation scheme. In the northern half and east of the island these use the permanent streams and rivers with well-forested catchments. The southern half of the island - particularly the populated western portion – does not have any permanent streams, the southernmost one being Vorani Creek, south of Wairiki. In this area, estate-level water schemes are based on collection and reticulation of water from small, high-level springs and rain-water collection. Areas south of Qarawalu are dependent on either rain-water collection or groundwater derived from bores in the Qarawalu area. Currently the first stage of the South Taveuni rural water project is being installed, which involves a sub-surface reticulation of bore water to houses and estates from Qarawalu to Ura (Figure 6). Future developments of this project will include reticulation to the rapidly expanding Delai Vuna area and to other villages to the south. In addition to these schemes, many coastal springs occur along the south and western coast of Taveuni and these are used at low tide in times of drought.

Locations of water supply and reticulation systems subject to differing degrees and types of hazard are the same as for buildings and population centres. Elements of the Taveuni system subject to the greatest hazard include the water bores and reticulation system in the vicinity of Qarawalu. Parts of this network and the bores are located within or adjacent to high flowage-hazard areas of hazard zone A (Figure 5).

Aside from physical destruction by lava flows or ground rupturing by earthquakes during eruptions, water supply and reticulation systems can be easily contaminated or blocked by ash falls. Both stream-fed and roof-collection systems are at greatest risk from contamination by ash falls and volcanic gases. Chemical contamination problems may include high acidity of water and excessive contents of fluoride, selenium, arsenic, mercury and boron (e.g. Cronin *et al*., 1998). Water turbidity is likely to be the major problem, with very heavy ash falls causing blockage of filters and pipes and interruption of water supply. These problems may affect on villages that are themselves out of the range of volcanic activity but have water-supply catchments high on the island's slopes and within areas affected by volcanic activity. Bore-water systems and systems using spring waters should not suffer such great contamination problems from ash fall. They may, however, experience some chemical change in water at some time after an eruption. In emergency situations, water derived from intertidal springs would probably be unaffected by volcanic activity.

6) Communications

Taveuni serves as a hub of communications for many islands of the Lau Group to the southeast of Taveuni. On Des Voeux Peak (Figure 6) is a communications station that relays signals from Taveuni and islands to the east, to stations on Vanua Levu and Viti Levu. Any event that should incapacitate the Des Voeux Peak station would render not only Taveuni but also many islands to the east of Taveuni without effective communication.

The Des Voeux Peak station lies directly within the axial portion of hazard zone A, and is subject to high degrees of hazard from all near-vent volcanic phenomena as well as substantial tephra falls. Near-vent explosions, ballistics, ground rupturing, etc., will all physically affect on the communications tower and associated buildings. Ash falls from nearby or from greater distances are likely to short-circuit electrical systems, interfere with signal-transmissions, and interfere with the operation of the diesel generators that power the station.

Communications networks within Taveuni include a basic telephone-line network that covers most of the island and a local radio network. This system is highly susceptible to temporary damage by direct volcanic activity, knocking over telephone poles, etc., and cutting off communication to portions of the island. Similar damage is frequently experienced during cyclones. Although these systems can be repaired within days, during volcanic emergencies the lack of communications could prove highly hazardous in the first few days of an eruption – particularly if road access is cut off by volcanic events. Other communication systems such as radio-telephones (RT and CB) may still be operational (ash falls can interfere with radio signals), although these may not be available to all communities.

7) Roading and vehicular transport

Taveuni has a network of mostly unsealed roads that service villages along the coastal portions of the island (Figure 6). The main road extends down the entire length of the western coast of Taveuni but does not completely encircle the island. Parts of this roading system are currently being upgraded, such as the re-modelling and sealing the main road from the airport in Matei to the administrative centre of the island at Waiyevo (Figure 6). Later stages include remodelling and sealing other portions of the main road.

The main road and branch roads intersect in numerous places within the flowage-hazard portions and axial parts of hazard zone A (Figure 5). In addition, much of the southern Taveuni road system is within hazard zone 1, of highest tephra-fall hazard. Hence, the integrity of the roading network is subject to a high degree of hazard. Road access is likely to be cut by lava flows, lahars, and block-and-ash flows, in addition to damage or burial in places from near-vent explosion, ballistics and hydrovolcanic activity. Tephra falls will probably generate shorter-term disruption because tephra is more easily removed from roads, or can be driven over in some circumstances.

There is no alternative road access to the single main route for the island's communities. This increases the vulnerability of the roading system to volcanic impacts, when the locations of the only large-vessel port facilities, Airport and Hospital are considered (Figure 6). If road access is cut at any point along the SW coast of the island, all populations south of the damage are isolated from the essential services to the north. Given that many eruptions on Taveuni may continue for several months and perhaps years, continued lack of road access would generate long-term economic problems for residents in the south of the island.

8) Fuel supplies and storage

Most fuel (petrol and diesel) arrives and is stored at the Shell fuel depot on the coast at Waiyevo (Figure 6). Some diesel fuel also arrives in tanks on the weekly ferry ships. Other major fuel stores include tanks at filling stations in Somosomo and Naqara.

Fuel supplies in the Somosomo/Naqara area are located within or near to a portion of hazard zone A and are subject to a high degree of hazard from lava, lahar and block-and-ash flows. The main Waiyevo store is located within a zone of moderate hazard (zone B) from the flowage events. All three storage sites are located within the highest hazard zone for tephra falls >20 cm.

Volcanic effects on fuel stores may include damage and rupture of tanks by lava flows or lahars, or ignition of fuel by hot tephra, lava or eruption-related fires. These effects may result in serious explosions in the areas of major fuel storage, particularly at Waiyevo. There may also be spillage of large amounts of diesel fuel onto the surrounding coastal areas.

Volcanic activity will also disrupt the continuity of fuel supply – which is essential to services such as the Des Voeux Peak communications facility, the hospital operations and businesses, and homes.

9) Shipping and port facilities

Taveuni is serviced three times per week by “roll-on, roll-off” ferry services to Vanua Levu and Suva, which dock at the only port facilities on the island, between Somosomo and Waiyevo (Figure 6). Fuel tankers arrive periodically and although not docking, pipe fuel ashore at the Waiyevo fuel depot. In addition, a daily and sometimes twice daily smaller ferry service runs from a nearby wharf to Buca Bay, Vanua Levu. These services are essential to the economy of the island, transporting all agricultural produce to Suva and further afield. If access to port facilities or availability of shipping were hindered by volcanic activity, major economic losses would be incurred on Taveuni. In addition, food and fuel imports are essential to the island.

The main large-vessel dock is subject to a high degree of hazard from lava, lahar and block-and-ash flows, being located within part of hazard zone A (Figure 5). The nearby alternative docking site is within range of secondary explosions if lava flows enter the sea at the main dock site. Shipping routes west and south of Taveuni may pass within the tephra hazard zone 2 and be subject to tephra falls of >10 cm. Lesser falls may also be experienced by shipping at greater distances from Taveuni.

The main docking facility may be inundated by lava flows or laharic debris, rendering it unusable. Nearby lava flows may also generate hazardous explosions upon entering the sea, rendering use of the docking areas highly dangerous. Tephra falls on ships in the vicinity may interfere with radar and navigation systems, electrical equipment and outside machinery. Fine tephra may also cause respiratory problems in people on board as well as accelerated corrosion of ship metal surfaces.

10) Air transport

Taveuni has a single airport, located in the Matei area (Figure 6) that receives several daily passenger/freight flights from Suva, Nadi, Savusavu and Labasa. The prop-driven aircraft use flight paths, above the island and along the east coast and along the west coast of Taveuni.

The airport itself is subject to a low risk from flowage volcanic hazards, although it is within a zone of moderate tephra-fall hazard (tephra hazard zone 2), with the potential for falls of >10 cm. Domestic air routes to and from Taveuni are subject to a relatively high degree of hazard from tephra and volcanic gases during eruptions. Aircraft flying through ash clouds are subject to damage by abrasion from ash as well as potential clogging of air filters and electrical, and navigational system disruption. In cloudy weather, tephra clouds may be hidden and difficult to avoid. Tephra fall on the airport runway would probably close down its operations temporarily.

International jet traffic that flies over Taveuni may also be at risk from ash clouds that may reach up to 11 km high. Several instances of jet engine failure are recorded from flights passing through volcanic ash clouds (e.g. Johnson, 1988).

11) Agriculture

Agriculture, mostly the production of dalo (taro) and yaqona (kava), is the main economic activity of the island. Other important crops include coconuts, cassava (tavioka), and beef cattle. The greatest proportions of most crops are exported to other parts of Fiji and overseas, mostly by sea but with higher-value crops (yaqona roots) by air as well. At current prices, individual yaqona plants are worth >F$150 at maturity (4-6 years), while individual dalo are worth F$1-3 at maturity (7-8 months). Large areas all over the inhabited areas of Taveuni are currently planted in both these crops and this amounts to tens of millions of dollars - for many people this is their largest investment.

Agricultural land suffers the same degree and distribution of volcanic hazard as population and buildings on the island. However, agricultural land often stretches onto the upper slopes of the island toward its central ridge and closer to the probable sources of future volcanic activity. Agricultural areas subject to the greatest hazard from volcanic activity include western areas south of Somosomo, and the entire inhabited portion of southern Taveuni.

Most crops are susceptible to damage from volcanic activity. Aside from areas burnt and buried by lava flows, large additional areas can be damaged by ash falls and volcanic gases. Ash falls of over 10 cm are likely to kill or severely damage most crops, except coconuts. Even much lesser falls at greater distances downwind of the vent can have substantial effects on many crops. Broad-leaf plants such as dalo and yaqona are especially susceptible to volcanic-gas aerosols and ash fall. The high levels of acidity in gas aerosols and even very thin ash fall can cause severe burning of the plants, which can lead to death of the plant or a long period of slow growth and recovery.

Volcanic activity may also halt exportation of agricultural produce, by blocking access to port facilities, destruction of port facilities or halting of shipping in the area. Any disruption to agricultural exports from the island would seriously affect its economy, particularly if the eruption or its effects were of long duration.

12) Tourism

Taveuni currently receives 5000-8000 overseas visitors per year (Corbett, pers. comm. 1999). At present there are 24 resorts, hotels, boarding houses and camping grounds on Taveuni, with a total of approximately 267 beds. All of these are relatively small-scale developments, with the largest having 28 rooms. Most of the resorts are concentrated at the northern end of the island in the vicinity of the airport (Figure 6).

Two of the tourist accommodations are located within the highest zone of flowage hazards in Naqara, whilst another 7-8 are located in moderate hazard areas (zone B), 6 along the south-western coast of the island and 1-2 in the Matei area. The remaining resorts and accommodations lie within areas of relatively low ground-based hazard. Similarly, 8 sites lie within the tephra hazard zone 1 and are potentially subject to >20 cm of tephra fall, whilst the remaining 16 sites all lie within tephra hazard zone 2.

Most of the tourist accommodation on the island is built to a relatively high standard. However, no building will resist lava, lahar or block-and-ash flows. In addition, heavy ash falls can collapse roofs of even well-constructed buildings, particularly if the roof pitch is low. Other volcanic effects may include contamination of water supplies and swimming pools, disruption of electricity limited availability of local produce and also imported foods.

Volcanic activity could potentially have serious effects on the tourism industry on the island. Conversely, if eruptions were not too disruptive and large, they may provide a boost to tourism on the island – by increasing its international exposure and by interest in viewing (safely) an eruptive spectacle.

13) Other economic activities

Other economic activities could also be severely disrupted by volcanic activity. These effects would be additional to any physical building or equipment damage sustained. Disruption to imports, transport routes, electricity and communications could severely affect many local transport, taxi, retail and brokering businesses. If agricultural exports were also affected, island cash-flows would be severely reduced, and this would be passed on to retail businesses on the island.

EXAMPLES OF PROBABLE ERUPTION SCENARIOS

The following are three examples of eruption scenarios for Taveuni. These are NOT predictions of the locations of the next eruptions on the island but they are examples of what MAY happen in a future eruption on Taveuni. All are based on past eruptions on the island and exhibit the magnitude and types of process expected in future activity based on geologic study of past events.

The three scenarios were designed to cover the range of volcanic processes likely on Taveuni, as well as covering different areas that are most likely to be affected in future eruptions. Each scenario has a differing precursory sequence and duration. The eruption styles are quite different and reflect the variation likely between eruptions on the island. Following the eruption sequence, some of the possible effects or consequences of the eruption are listed with respect to population and infrastructure on the island.

1) Scenario 1 – Qarawalu area cone-building eruption (Figure 7)

1A) Sequence of events:

Day 1 – A magnitude-3.6 earthquake is recorded by the Fiji Seismograph Network. The earthquake was located beneath Taveuni at a depth of approximately 20 km.

Day 5 – Locals in Qarawalu and Delai Vuna report lots of small earthquake shakings, mostly felt at night while people are lying down. Dogs and cattle are behaving strangely.

Day 8 – Reported shaking from the area is increasing to the point where small quakes are happening every 15 minutes. Most people on the island are talking about these events.

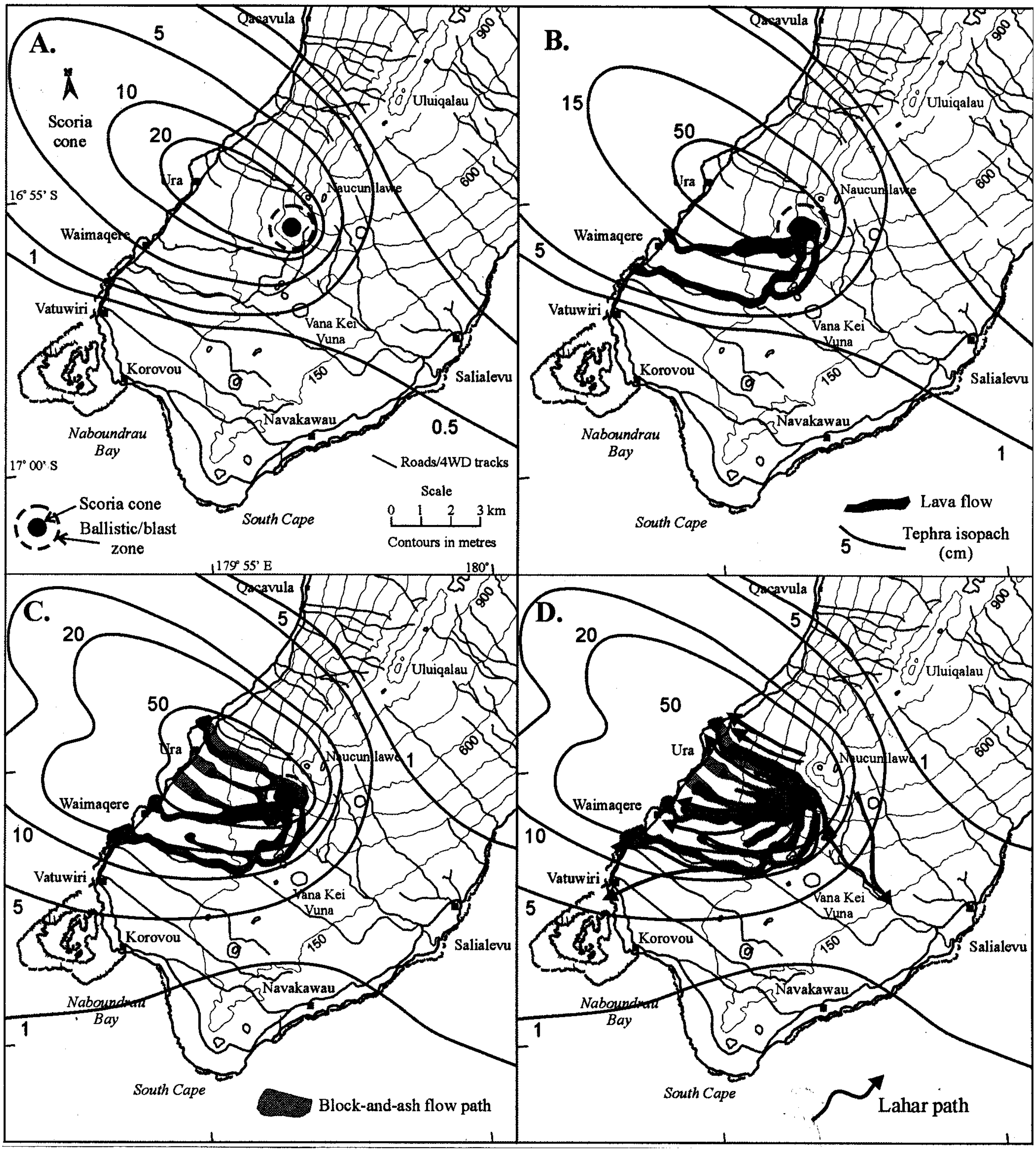


Figure 7: Stages in the development of Eruption Scenario 1 in the Qarawalu area. (A) situation at the end of day 12, (B) After day 21, (C) After day 36, (D) Situation at the end of the eruptive activity.

Day 10 – 0815 hrs; a magnitude-3.8 earthquake is recorded by the Fiji Seismograph Network; it is located 10 km beneath the southern end of Taveuni.

– 0830 hrs; steam is sighted in the bush area above Waioba; the initial reports were that it looked like smoke from a fire.

– 1045 hrs; hunters returning from the hills above Waioba report feeling lots of shaking and hearing loud booming noises.

– 1135 hrs; booming noises can be heard in the area between Ura and Salialevu. A large column of steam is seen briefly before clouds close in over the central hills and block the view.

Booming noises continue throughout the night.

Day 11 – 0615 hrs; a fine layer of pale muddy ash is reported, covering the Ura and Waimaqere areas; the layer is 2 mm thick on a car roof at Ura.

– 0620 hrs; the view onto the hills is clear; there appears to be a bare grey area within the forest above Waioba. A column of dark black ash rises 500 m above the hills, red streaks are seen within the column until the sun rises completely.

– 0946 hrs; black scoria ash, including pea-sized grains, begins to fall on observers at Ura. The ash cloud on the hills has reached 3 km high.

– 1410 hrs; the column of ash has grown to about 6 km high; the upper part appears thinner and is bent toward the east, while the thick, dark lower portion appears to be bent to the west.

– 1530 hrs; observers from upwind locations (to the east) note that a black scoria cone of up to 400 m across at its base and 70-80 m high has developed in the vent area.

Ash eruptions continue throughout the day and following night, with tephra falling heavily in the Ura area. Light tephra falls occur also in Waimaqere and Salialevu. Throughout the night eruptions continue, booming is heard throughout the evening; shaking and earthquake activity appears to have subsided. Observers witness a red-streaked eruption column with large red ballistics travelling on arching pathways. Activity appears to burst and subside on regular intervals of 15-30 minutes. Flashes of lightning are seen periodically in the ash clouds above.

Day 12 – (Figure 7a) Ash eruptions continue, semi-continuous eruption columns are produced up to 6 km high, each is then blown to the west at low levels, before the next is produced. A large but dispersed cloud of ash in the upper few km of the column hangs above the cone and stretches toward the east at high levels. Fine ash fallout to the east has amounted to 0.5 cm of total fall at Salialevu. At Ura, ash fall has reached 20 cm in thickness, with some tephra particles up to 15 mm diameter. Time between vigorous periods of ash production increases to 30-50 minutes, and the eruption column at low levels is sporadic. The upper-level ash cloud stretches almost continuously for up to 30 km eastward before disappearing.

Day 13 – A sudden increase in the vigour of eruptions, with frequent loud explosions; a stable eruption column up to 8 km high persists for most of the day. Wind has slightly changed and ash begins to be deposited more heavily on the Waimaqere area.

Day 14 – Ash eruptions diminish in vigour, an eruption column of up to 3 km is present on and off during the day.

– 0530 hrs; Bright red lava begins to fountain from cracks that have appeared beside the base of the scoria cone (which is now >100 m high and 500-600 m in diameter).

– 0630 hrs; Cones of agglomerate grow on the up-slope side of the fountaining lava fissures and aa lava proceeds to flow downslope toward Qarawalu. The flow front is estimated to be travelling at 5 km/hr. Fires are started on the lava margins as the flow bulldozes its way through forest.

– 0650 hrs; The lava flow has slowed to 3 km/hr but has reached the first of the cultivated areas up-slope of Qarawalu. Fires continue to spread in the surrounding forest.

- 0730 hrs; Other lava flows are noticed, one within a side catchment travelling toward Qarawalu, the other flowing toward Waioba. These flows are estimated to be moving at 4-5 km/hr.

- 0815 hrs; Lava has passed through most of Qarawalu, the later side flow has joined the main lava flow in the Qarawalu direction and the flow front is now moving toward Waimaqere (velocity estimated at 2-3 km/hr). The first of the water-well installations is only 1 km away, and the flow front is now 80 m wide.

- 0915 hrs; Reports are that lava has overrun one of the well sites and storage tank facilities. A large explosion followed by many small ones occurred as the water tank was breached by the lava flow.

- 1015 hrs; Lava crosses the road and flows toward the sea north of Waimaqere, after having flowed through Waioba estate. The flow front is estimated to be 100-120 m wide.

- 1045 hrs; Lava is entering the sea north of Waimaqere, local explosions are in progress with ejecta being thrown 200 m into the air. A large steam cloud has formed and local observers are complaining of eye and throat irritation in the area.

- 1530 hrs; Lava enters the sea south of Waimaqere, having crossed the road 30 minutes before; the flow front is 50-60 m wide. Steam clouds and explosions begin similar to those that continue from the flow two kilometres to the north.

Days 15-21 (Figure 7b) Lava continues to be emitted throughout the next few days, with new pulses beside and overriding the earlier flows. Flows enter other catchments north of Waioba estate. Another flow arrives at the sea on Day 19, further acidic steam generation and local explosions ensue. The main flows remain as aa-type flows. Tephra eruption continues unabated, but with eruption columns rarely exceeding 3-4 km in height. The Ura area now has 40-50 cm of tephra cover, while Waimaqere has 15 cm.

Days 22-29 Minor emissions of lava continue, ash eruptions mostly cease. Occasional small ash columns are generated to 1 km high. Gas and steam clouds continue to be emitted forming a gas- and steam- dominated plume up to 3 km high at times. Fine ash falls over Waimaqere and Ura.

Day 30 – A major resurgence of activity with a black tephra column up to 7 km high generated. Heavy tephra falls occur at Waimaqere (10 cm in the first two hours), moderate ash fall continues at Ura and light falls begin at Vatuwiri.

Days 31-35 A resurgence of lava emission, large slow-moving blocky aa flows descend along several flow paths toward the western coast. Qarawalu is again affected, with flows entering the sea in three locations north and south of Waimaqere. One of the lavas is apparently flowing through a newly formed lava tube into the sea. Ash falls continue from a 5-km-high column, concentrated in the Waimaqere area. Light falls drift over several parts of the southeast coastal areas of Taveuni and further out to sea east of the island.

Day 36 – (Figure 7c) Collapse from the fronts of two large aa flows sends red-hot blocks of lava and smaller fragments cascading down the islands slopes and across Waioba and Ura Estates. These hot block-and-ash flows travel to the coast. They are estimated to be travelling at 30 km/hr near the coast.

Days 37-68 Ash and lava emissions continue intermittently. Small lava flows stack up and periodically surge downslope. Ash continues to accumulate in the Waimaqere and Ura areas, with light falls in most parts of south Taveuni. Cooling lava flows occasionally crack and release gases and steam.

Day 69 – (Figure 7d) A small ash and gas cloud is generated 500 m above the scoria cone, which is now 750 m across at its base and 150 m high and surrounded by several 50-m-high agglomerate cresent-shaped part-cones.

No further activity is observed from this vent. In total, 10 million m^3 of scoriaceous tephra was produced, and mostly distributed to the west on land (fine-grained falls also occurred for long distances to the east). Tephra >20 cm thick covered an area of 14 km^2, and falls >10 cm covered

20 km^2. Around 6-8 million m^3 of lava was also produced during the eruptions, covering a final area of around 10 km^2.

3 months later – heavy rains remobilise large amounts of tephra from the upper slopes of the island, generating lahars that flow down several pathways and spread out onto coastal areas between Ura and Vatuwiri. These flows sweep away many pre-existing and temporary shelters in the area. Intermittent lahars follow heavy rainstorms over the next few months. Later flows become smaller and more dilute-watery floods.

1B) Possible consequences

The eruption outlined is a geologically typical event of the cone-building style of eruption on Taveuni. The potential consequences to life from this eruption are highly dependent on the emergency response to it, conversely, property damage is essentially unavoidable. Consequences are estimated in the absence of any control or emergency management on the island.

Population

- The precursory earthquakes may have generated a lot of unease in the surrounding communities, but probably very few people leave the area.
- Self evacuation of most people from the Ura, Waimaqere, and Qarawalu villages occurs only as lava flows pass and fires are started. Most people probably travel on foot to villages in the south (e.g. Korovou) or to the east (Salialevu). Some people working in isolated high gardens may be trapped by fires. Other injuries (mostly burns or abrasions) are sustained as people try to recover other property or crops from the area. Domestic animals, including cattle in the Ura and Waioba areas, are left behind in the rush to escape the lavas and fire. In the panic to leave many people take only their most precious possessions including saved money.
- During the ensuing days and weeks some people return to parts of the devastated areas to recover property and to loot abandoned houses and farms.

- Later, surviving yaqona is harvested indiscriminately within the eruption-affected areas, most of it looted by fit and opportunistic men. Some injuries are sustained by these people in the eruption area, from heavy tephra-particle impacts or burns from fires or residual heat in lava and tephra.
- Some people travel up and down from northern Taveuni, but can only do so by small boat, and at times when the weather and ash falls do not prohibit it.
- Water supplies become stretched once the water wells and installations are destroyed by lava, and more pressure is placed on the southern village supplies by the influx of refugees.
- Food shortages of some items begin within the second week of the eruption; only limited supplies can be brought in by light boat.
- Friction develops later on once looting of yaqona is discovered.
- With road access to the north blocked for up to a year by cooling lavas, the economy and livelihood of most people in south Taveuni is severely threatened. A drastic reduction in agricultural earnings ensues, not only from loss of existing crops, planting material, houses and possessions, but also from initially unaffected people who can no longer easily transport their goods to port facilities in the north and onward to sale.
- Later lahars sweep away several people that have reoccupied parts of the area between Ura and Vatuwiri. These events were preceded by no warning, except the rainfall. Several people are swept away or buried by the lahars and many sustain abrasion and laceration injuries during the first series of flows. Later lahars were anticipated although crop and shelter loss is still commonly sustained.

Infrastructure and agriculture

- Fires, tephra falls and lava flows destroy crops throughout large areas between Qarawalu, Ura and Vatuwiri.
- Lava flows destroy water-well installations, storage facilities, and pipelines in the Qarawalu-Waimaqere area. As a result of this water supplies are cut to all areas supplied by the scheme.
- Lava flows block the main coastal road northward in three locations. Continuing flows, cooling earlier flows and topography make it impossible to establish an alternative vehicle route northward. Access by foot northward is also impossible.

- Houses in the Qarawalu and Waimaqere areas are destroyed by lava flows and fire. Heavy tephra falls also collapse many houses in the entire area, including Ura.
- Much formerly arable (and valuable) land is effectively permanently (in terms of current economic criteria) destroyed by inundation of lava, lahar deposits or tephra falls exceeding 50 cm.
- Later lahars destroy other areas of cropland and additional houses and shelters.

2) Scenario 2 - Upper Lovonivonu lava eruption

2A) Sequence of events

Day 1 – A magnitude-4.5 earthquake is detected by the Fiji Seismographic Network; it is located 30 km beneath Taveuni. It is not immediately recognised as being volcanic in origin. This is felt on the island.

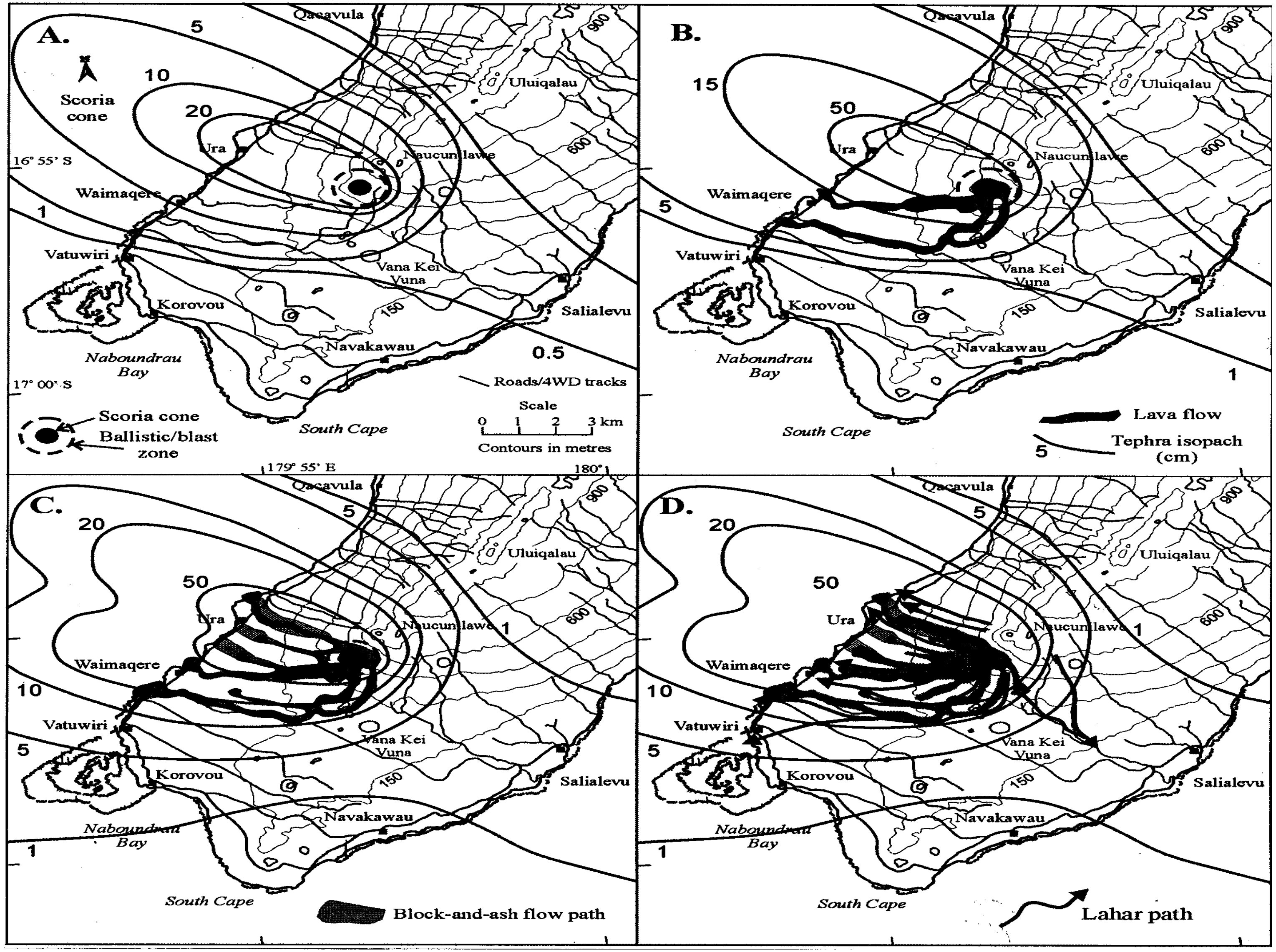
Day 14 – A magnitude-3.8 earthquake is detected by the Fiji Seismographic Network, located below Taveuni at a depth of 20-25 km. This is felt on the island.

Day 26 – Three earthquakes (Mag 3.6-3.7) are detected 15-20 km deep beneath Taveuni. Two are widely felt on the island.

Day 33 – Five earthquakes (Mag 3.5-3.7) are detected at shallow depths (10 km) beneath central Taveuni. All are felt widely on Taveuni. Some degree of unease is felt in the community, although volcanism is not considered to be a cause or eventuality.

Days 33-40 Seven further earthquakes (Mag 3.5-3.8) are detected at shallow levels beneath central Taveuni. The location of these is pinpointed to between Des Voeux Peak and Lake Tagimaucea (Figure 8a). Many smaller earthquakes (not detected on the Fiji Seismographic Network) are felt by local residents in central Taveuni. The frequency of these earthquakes builds to 150 per day on Day 40.

Figure 8: Stages in the development of Eruption Scenario 2, in the Waiyevo area of Taveuni. (A) Situation at day 42, (B) by day 49, (C) First clearance in weather on day 51, (D) Final situation following eruption.



Day 41 – The frequency of earthquakes rises, 300 shakes are felt during the day in central Taveuni, only a few are recorded instrumentally by the main Fiji Seismographic Network.

– 2315 hrs, booming noises are heard by people living between Tutu and Somosomo (Figure 8a). The noises are thought to be coming from the hills near Lake Tagimaucea. The noises continue throughout the night although nothing is seen on the hillside - heavy clouds cover the area.

Day 42 – 0545 hrs, booming noises have subsided but still occur occasionally. Nothing is seen on the hillsides – heavy cloud still cloaks them and rain begins to fall. People consider the noise to be some type of strange thunder storm – although no lightning was witnessed. The ground shaking has stopped, apart from a few isolated events.

– 0715 hrs, occasional muffled booming noises still occur. Smoke is mixed within the rain clouds and a strong smell of smoke and burning is detected by people working on gardens on upper Tutu Estate and up-slope from Tavuki Village.

– 0830 hrs, scattered rain continues and the cloud cover remains thick and low. Burning and smoke is noticed by all people living between Tutu and Somosomo.

– 1145 hrs, an advancing pahoehoe lava flow is reported above gardens at Waitavala. The flow is around 1 m thick, with a front 60 m wide. Trees are left standing within the flow but are burning. Limited fires are starting at the margins of the flow, but due to the saturated vegetation and sporadic rainfall they die out quickly. The flow is estimated to be moving at 5 km/hr.

– 1412 hrs, the lava flow on Waitavala has reached one of the side roads in the area, razed two houses, and buried or burnt an entire small valley of gardens. It is flowing at approximately 2 km/hr, across a front 50 m wide. A second pahoehoe flow is reported at the top end of Naiyalayala Estate, with a flow front 80 m wide, flowing at 4 km/hr. Local small explosions are occurring on both lava flows, where they are flowing into water pools within stream beds. Hot rock debris and steam are blasted to within a 150 m radius. People on Waitavala and Naiyalayala report strong sulphurous smells, sore throats and eyes. Some older people are having trouble breathing.

Smoke and gases are remaining at low levels. The wind is very light or absent and the thick cloud cover remains.

– 1730 hrs, (Figure 8b) both the Waitavala and Naiyalayala lava flows have crossed the main coastal road and are flowing into the sea. The former flow has buried the roll-on roll-off ferry landing and the Naiyalayala flow has blocked access between Waiyevo and Wairiki villages. More gardens and a few more houses have been destroyed. Local explosions are in progress at the coast from both lava flows. Rock debris is blasted 150 m around the flow fronts which are both around 60 m wide. A cloud of sulphurous-smelling steam hangs over the area between the two flows, widespread reports of eye and throat irritation continue.

– 2030 hrs, under darkness the two flows are streaked with bright red, and their paths can be seen part-way up the slopes, small localised fires are seen beside both flows. Clouds still block the view more than half way to the top of the island. The calm conditions remain and the air in the region is laden with sulphurous steam and gases.

– 2203 hrs, through a break in the clouds there appears to be a line of flame high on the slopes. There also may be what looks like another lava flow high above Waitavala, and perhaps some more red areas further to the north.

Day 43 – 0612 hrs; Rain continues to fall on the higher slopes and the winds are very light or absent. Visibility to the high slopes is completely blocked by clouds. A second lava flow is confirmed on Waitavala, it is flowing in a catchment to the north of the first flow and is within 2 km of the coast. Lava continues to flow into the sea from the first two flow paths. Clouds of strong sulphurous gases, steam and smoke remain within the area between Wairiki and Somosomo. Light drizzle is falling in the near coastal areas.

– 0845 hrs; Several further flow pulses are overtopping the first two lava flows. The overtopping flows are highly fluid and 0.5-1 m thick. They are flooding outside the margins of the initial lava and widening the area of inundation for each of the flows to c. 120-150 m. Three other thin pahoehoe flows are reported above Naiyalayala and Waitavala.

– 0852 hrs; The northern Waitavala lava has joined the main flow path and there is a strong resurgence of lava flowing into the sea. A lava delta has formed at the site of the former ferry landing. The delta is estimated to be 300 m wide and 150 m broad (from the shore seaward). A smaller lava delta of 200 m wide and 80 m broad has formed where the Naiyalayala flow enters the sea. Steam generation and local explosions at the active delta margins continue unabated.

Later during the day several more thin lava flows overtop the initial ones, flows in other pathways then join the two main channels. Rain continues, visibility remains low, steam and gas production remain high.

Days 44-49 Thin pahoehoe lava flows continue in the two main catchments – multiple flow threads occur, several lava tubes are in use, some collapse, with lava spilling out. The areas buried by lava widen as the main channels are almost completely filled in. The Naiyalayala lava delta builds to 600 m wide and 250 m broad, while the Waitavala delta is now 1 km wide and 300 m broad, almost filling the entire bay area. Steam and gas production continues with sporadic local explosions at the active margins of the lava deltas. Rainfall or cloudy conditions persist.

Day 50 – 0300 hrs; The clouds clear from the upper part of the island and a south-easterly wind rises. Observers report a long line of fire (over (one) 1.5 km) across the upper slopes, near the top, above Waitavala. Several red-streaked lava flows emanate from this toward Naiyalayala. Another, shorter line of fire (0.5 km) is reported at about the same level of slope, but above Somosomo; there appears to be a lot of red-streaked lava or fire within a large area immediately below the line of fire.

Lava continues to flow down the two main catchments; much steam and gas is still produced on the enlarging lava deltas, but is blown strongly out into the Somosomo Straits. For the first time since the lava started the air is not strongly laced with a sulphurous smell causing irritation to eyes and throats. Fine ash begins to fall over the area later during the day, but falls do not exceed 1 cm.

Day 51 – 0956 hrs; A large lava flow is reported travelling rapidly toward Somosomo at 10 km/hr. The flow is presently c. 3 km from the village. The pahoehoe flow appears c. 40-50 m wide and is flowing down a catchment that leads initially past Naqara. It seems that that large area of lava on the upper slopes was ponding there and was suddenly released by a small slope collapse.

– 01045 hrs; The new pahoehoe flow has reached Naqara, much steam and many small explosions are generated when the lava meets large pools of water in the stream, which largely dried up this morning.

– 01130 hrs; (Figure 8c) Much of central Naqara is razed by fire and inundated by lava up to 1 m thick. Lava begins to enter the sea, generating more local explosions and sulphurous steam.

Lava continues to flow at a lesser rate on the Naqara flow, while lava flow continues unabated in the other two catchments.

Days 51-85 hin stacked lava flows continue in all three catchments. The Naqara lava stops flowing on Day 59, after fire-fountaining ceased on the upper slopes in the smaller northernmost fissure area. A subsidence in the fire-fountaining and lava emission also occurs in the larger southern fissure at this time. The southern fissure remains active but with strong variations in the rate of lava emission. New thin blanketing pahoehoe lava flows occur sporadically in the two southern catchments. The final size of the Naqara lava delta is 200 m wide and 50 m broad. The Naiyalayala and Waitavala deltas continue to grow, with the latter having almost entirely filled the former bay. On calm days, particularly those with low cloud, large clouds of highly irritating sulphurous aerosols drift between the Wairiki and Somosomo areas. On other days, light ash falls occur, the maximum total ash thickness is c. 1 cm, accumulated throughout the entire eruption, most areas receive only a few mm.

Day 86 – 0415 hrs; a thin lava flow, diverging from the Waitavala area flows into the Shell Fuel storage area at Waiyevo. Several large explosions ensue as the large storage tanks are successively reached by the lava. Widespread fires develop and spread to neighbouring buildings. Sporadic explosions continue during the day as drums of fuel are ignited by the lava.

Days 87-93 Lava flows continue in the Waitavala and Naiyalayala catchments, although rates of lava emission die off considerably along the remaining fissure zone. Only a small portion at the south end of the zone remains active by Day 93.

Days 94-102 Small-scale lava flows continue in the Naiyalayala catchment; rates of lava emission die off and eventually cease by day 102.

No further eruptive activity is recorded at either of the two fissure zones. In total an area of 20 km^2 is inundated by lava flows (Figure 8d). Three large new lava deltas are formed, the Naqara (200 x 50 m), the Waitavala delta which fills the entire bay that was present formerly and measures 1500 x 500 m, and the Naiyalayala delta (2100 x 400 m). Small amounts of tephra cover the area between Somosomo and Wairiki, but total fall thickness is barely noticeable in most places, and built up to 1 cm in others.

2B) Possible Consequences

Once again a situation with limited emergency management support is considered. Consequences of such an event are highly variable, depending on human behaviour, meteorological conditions and volcanological phenomena experienced.

Population

- ☐ The precursory earthquakes may have generated a lot of unease in the surrounding communities, but probably very few people leave the area.
- ☐ The loud booming noises in the night that heralded the start of the eruptions were frightening, but because of the poor weather many people think that it was due to a thunderstorm.
- ☐ The first lava flows cause self-evacuation of people in their path, although the main villages are probably not evacuated.
- ☐ Once it is known that the Waiyevo area is going to be isolated from the north and south – it is probably evacuated. Some government staff and hospital staff remain during the days with access in and out by boat if possible with weather conditions and extent of offshore explosions from the lava deltas. However,

because the weather is so bad, not much is known about what is going on. Hence many people decide to remain and are then trapped within the area.

- Many evacuees probably head to either Somosomo/Naqara or Wairiki.
- Naqara and parts of Somosomo are self evacuated once the lava is known to be arriving in town. Many people do not leave their businesses until the lava is almost upon them. Some people remain trapped between Naqara and Waitavala and need to be extracted by boat. Several people sustain injuries trying to rescue property from shops and homes (mostly burns).
- Domestic animals and most possessions are left behind in the rush to leave – the flows moved very rapidly.
- During the ensuing days and weeks there is a strong desire in some people to return to parts of the devastated areas to recover property and to loot from abandoned shops, houses and farms. However, the only access into the Naqara and Waiyevo areas is by boat, and much of Naqara is razed.
- Since the time of lavas entering the sea, there are widespread complaints of eye and throat irritations throughout the area. Some older people and those with Asthma or other respiratory conditions find it increasingly difficult to breath.
- Fires tend to cause no great problems, the area and weather being so wet that most are dampened out.
- Over the following days and weeks, surviving Yaqona is harvested indiscriminately within the evacuated areas, most of it looted by fit and opportunistic men. Some burns are sustained.
- Water supplies in the isolated Naqara and Waiyevo areas dry up once the lavas have passed, and roof-fed water supplies throughout the entire area become contaminated by sulphuric acid and other chemicals from the volcanic gases that are continually generated at the lava deltas.
- Food and fuel shortages begin within the second week of the eruption, only limited supplies can be brought in by light boat, large boats can initially land at the second wharf area, but as the Waitavala lava delta grows this also becomes impossible.
- Friction develops later on once looting of yaqona and other property is discovered.

Infrastructure and agriculture

- Lava flows and limited fires destroy crops throughout large areas between Qarawalu, Ura and Vatuwiri.
- Volcanic gases and acidic aerosols damage crops over a further wide area in the days-weeks of the eruption.
- Road access to the Hospital is blocked from an early stage, fuel supplies also run low there – eventually it becomes impossible to keep it running and any patients must be treated elsewhere.

- Access to port facilities from the south is blocked at an early stage, later events also block access from the north as well as rendering the two wharves unusable. Hence the economy of the entire island is seriously affected. There are widespread shortages of fuel and some food items. Cash returns on all produce stops until alternative docking facilities for large ships are established in areas both north and south of the eruption effects.
- The shops and businesses and government activities cease completely in the Naqara and Waiyevo areas. These are the main areas of shops and services on the island.
- The telephone exchange in Waiyevo is abandoned once power supplies can no longer be maintained.
- Road access to airport facilities in the Matei area is blocked to all people living in the southern half of the island. Flights are able to continue unabated because ash fall is very minimal.
- Lava flows block the main coastal road in three locations. Continuing flows, cooling past flows and topography make it impossible to establish an alternative vehicle route north-south. Access by foot or road is impossible until the lavas have completely cooled.
- Many houses are destroyed by lava flows, however areas within only a few metres of lavas remain unaffected.
- Much formerly arable (and valuable) land is effectively permanently (in terms of current economic criteria) destroyed by inundation of lava exceeding 1 m.
- Resettlement of the area may not proceed due to the large areas that are now barren. The government station may be moved to another part of the island (e.g. Matei, near the airport).

3) Scenario 3 – hydrovolcanic eruption, South Cape area

3A) Sequence of events

Day 1 – An earthquake of magnitude 4.6 is detected by the Fiji Seismographic Network beneath the south Taveuni area. Its depth is estimated to be 30-40 km.

Day 3 – Two earthquakes (Mag 3.5 and 3.7) are detected by the Fiji network at 15-20 km beneath southern Taveuni. In addition, other earthquakes are felt on the island although not instrumentally detected by the Fiji network.

Day 4 – Five earthquakes (Mag 3.5-3.8) are detected by the Fiji network at shallow depths beneath southern Taveuni (≤10 km). Frequent ground shaking begins on southern Taveuni, with small earthquakes spaced 45 min – I hour apart.

Day 5 – Three earthquakes (Mag 3.5-3.6) are detected by the Fiji network at shallow depths beneath southern Taveuni (≤10 km). Ground shaking in southern Taveuni is reported to be even more frequent, estimated at one event every 15 minutes.

Ground shaking becomes more frequent (shaking frequency is ambiguous) during the night, more than 300 events are reported before 0515 hrs on Day 6

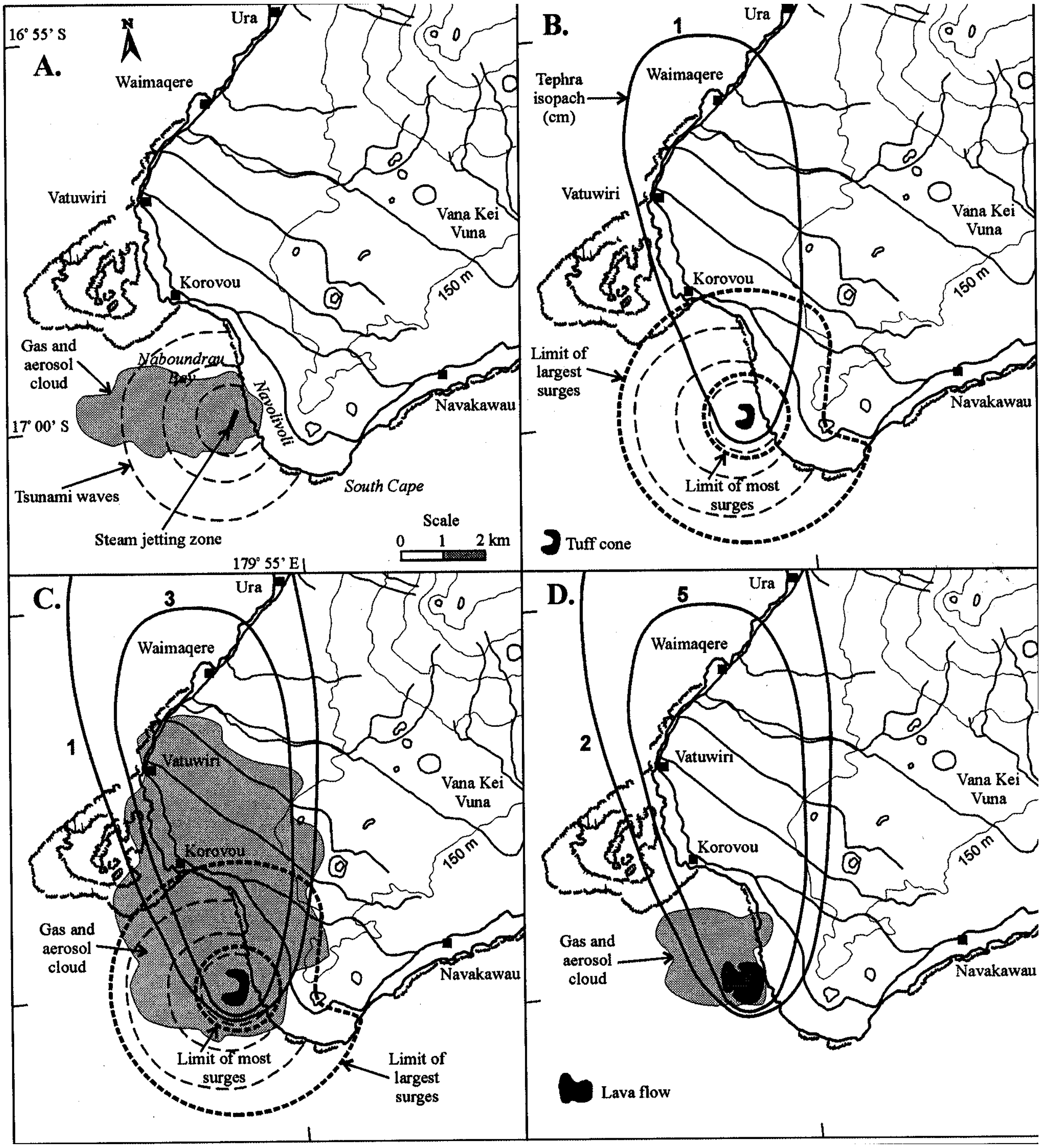
Day 6 – 0515 hrs; Ground shaking has become so intense in the Navolivoli area near South Cape that it has roused people living there who notice that either the tide is very low or that the land has risen in the nearby bay to form a new reef area.

– 0535 hrs; (Figure 9a) White jets of steam (up to 10 m-high) break the water in the centre of the bay. A large steam cloud develops and is blown to the west at about 500 m height. Circular waves up to 1 m high radiate from the vicinity of the steam jets.

– 0541 hrs; People standing and watching on the beach are overcome by a wave of pungent sulphurous gases.

– 0615 hrs; There is now a line, 200 m-long, of white steam jets. The sulphurous gases spread over nearby areas and overcome more people. A loud whistling sound is associated with the steam jets.

– 0628 hrs; Jets of black rocks up to 20 m-high begin from the centre of the steam-jet line, and progress until all the white steam is replaced by black ejecta. The rocks ejected steam in flight and some hiss upon entering the surrounding sea. Deep muffled booms are felt more than heard by observers. Waves generated from the line of jets reach 2 m high and slosh up as high as storm waves along the nearby coastline. The high steam column above the area has risen to 2 km in altitude and is being blown by light winds to the west. Gas emission seems to be less.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Vana Kei Vuna
Korovou
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Vatuwiri
Vana Kei Vuna
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Gas and aerosol cloud
Navakawau
Lava flow

Figure 9: Stages in the development of Eruption Scenario 3 in the Navolivoli area. (A) situation at 0628 hrs on day 6, (B) during the rest of day 6, (C) days 7-15, (D) the final stage of eruption on day 16.

– 0725 hrs; (Figure 9b) Jetting of black rock becomes more vigorous at the southern end of the line, and rock is blasted to 250 m above the sea level. A convecting column of steam and ash is generated above the erupting jets of black rock. A major blast of debris is sent 400 m into the air, and as this material falls to the surface it expands outward radially from the vent to sweep over the surrounding area at tremendous speed, as a mixture of rock particles, gas and steam. This blast or pyroclastic surge shreds the leaves from nearby trees and knocks over much vegetation and a few houses in its path. People near to the coast are killed by the moving rock clasts or vegetation and other debris swept along in the surge. People trying to escape and on the outer margins of the blast 500 m away from the vent are knocked over, some are injured, many can still escape to further away. Large sea waves are crashing up the shoreline and over the reef between Vuna reef and South Cape. The waves run up further than any known storm wave and damage a few houses close to the shore.

– 0800 hrs; The ash and steam column has risen to 5-6 km high and is blown to the northwest. Successive violent explosions send jets of black rock debris up to 800 m into the air. Collapse of these jets sends more violent pyroclastic surges out to over 1 km radially from the vent. More houses are damaged or destroyed. Yaqona crops are mown-over and swept away by the blasts, and other trees and plants are shredded and knocked over in places. Fine ash begins to fall in Korovou, Vatuwiri and Waimaqere.

The blasts increase in magnitude until 0900 hrs when a sustained tephra-rich steam column is generated to 8 km high. Ash continues to fall during the day over Korovou-Waimaqere, and builds up to 1 cm thick in Waimaqere. The column later collapses and reforms in a series of pulses. Each collapse event causes a large pyroclastic surge that radiates 2-3 km from the vent. Parts of Korovou are affected by the margins of the largest surges. Buildings are plastered with muddy ash, and some structures are damaged. Widespread damage to vegetation and crops ensues in the area. Most large trees remain standing, but with limbs removed, and plastered with muddy wet ash. By the end of the day a small tuff cone is built up around the vent, enclosing it on the near-shore side, but open on the offshore side.

Day 7 – (Figure 9c) Eruptions continue in a similar manner throughout the night and Day 7. Ash and steam columns are built to 6-8 km high on several occasions before collapsing and forming large pyroclastic surges. More-frequent smaller pyroclastic surges are generated from individual blasts of rock debris and gas from the vent. Tephra fall continues in the Korovou-Waimaqere area with falls building up to 3 cm in Waimaqere. Parts of Korovou are buffeted by the larger pyroclastic surges. Large sea waves accompany several of the explosions and pyroclastic surges, these run-up and damage low-lying coastal areas. A substantial island has formed in the bay of the vent, with an incomplete tuff cone (open to the SW) of 300 m diameter and 25 m height constructed around the vent.

Days 8-12 Eruptions continue in a similar manner, although the build-up and collapse of large ash and steam columns is less frequent. Many smaller blasts however generated hundreds of small pyroclastic surges radiating out up to 1 km from the vent. Intermittent tephra falls over Korovou-Waimaqere have deposited up to 5 cm of fine-grained muddy tephra. The tuff cone has grown to a basal diameter of 800 m and is now 50 m high. The cone remains incomplete and open in a westerly direction. During the latter days greater amounts of gas are released between the explosive eruption bursts. Gas and steam clouds drift over the SW edge of Taveuni.

Days 13-15 The frequency of explosions reduces further, until they cease completely. Gas is still vigorously released from the central vent and a 2-km-high gas and steam column remains.

Day 16 – (Figure 9d) The vent area is now dry and fire-fountaining lava emerges from it, with molten material thrust only 5-10 m high. The lava ponds in the central crater area before flowing into the sea through the gap in the surrounding tuff cone. Lava emission lasts for 8 hours and then ceases. Strong steam generation with sulphurous gases occurs where the lava enters the sea. Gas release from the vent has ceased.

From this point on, apart from a few later periods of gas release, no further activity is reported from this vent.

3B) Possible consequences

Once again a situation with limited emergency management support is considered. Consequences of such an event are highly variable, depending on human behaviour, the time of the eruption and length of warning time. In this case the warning period was brief, but this is highly possible.

Population

- ❑ The precursory earthquakes may have generated a lot of unease in the surrounding communities, but probably very few people leave the area.

- The few people that were living near the vent area and were on shore to witness the first blasts would have been killed.
- The rapidly enlarging blasts would have inflicted serious injury to several other people that were trying to flee.
- Populations on the extremity of the blast effects that may not have known about the eruption would also sustain injuries, mostly lacerations and abrasions.
- Survivors in the Navolivoli region would probably self evacuate as fast as possible once the initial blasts arrived. Most probably head to the closest village, Korovou.
- Tsunami waves associated with the explosions and surges may sweep out to sea a few people that are living in near-shore houses, others may sustain injuries.
- The later larger pyroclastic surges and tsunami waves may cause light injuries in Korovou. The southern part of the village is probably self-evacuated once the larger surges begin. Perhaps the entire village evacuates in the face of the loud eruptions, blast waves and ash fall.
- The eruption is only of short duration, hence, immediate food supply, water and shelter provisions are probably not critical. Evacuated people could be housed in school buildings at Vatuwiri and at villages further north.
- Injured people within the blasted areas would need to be rescued from the area and treated. This may endanger rescue parties entering the area.
- Gases and acidic aerosols cause widespread eye and throat irritations in the Korovou-Waimaqere areas.

Infrastructure and agriculture

- Houses in the Navolivoli area and parts of Korovou are damaged or destroyed by the pyroclastic surges and/or the associated tsunami waves.
- The blasts as well as acidic volcanic gases and aerosols damage crops over a wide area around Navolivoli.
- The main coastal road is blocked by fallen trees and scattered debris. During the eruption this road is also subject to extreme hazard from pyroclastic surges. There are alternatives to this road.
- Ash falls and acidic aerosols may damage electrical systems and generator engines in the Korovou-Waimaqere area.
- The land affected by pyroclastic surges is buried by deposits 0.1-0.5 m thick. Much of the area could be restored to production in a few years.

CONCLUSIONS AND POTENTIAL RISK MITIGATION STRATEGIES FOR TAVEUNI

That an eruption will occur on Taveuni one day in the future is almost certain. The question is more “When?”. With an eruptive history encompassing at least 167 events since 9500 BC, the average interval between eruptions is shorter than that used for planning for flood events in most countries. However the past frequency of eruptions on Taveuni tells us that rather than being evenly distributed, they tend to occur in bursts of several events in a short space of time. The intervals between these bursts may be anything up to 400-500 years. However, all is not truly quiet during these intervals either, the eruptions are merely more sporadic and isolated. Overall we can consider that whatever the intervals between eruptions are, between 60 and 400 years, there is a high probability of renewed activity on Taveuni within the next 100 years.

Another pertinent question on Taveuni is “Where?”, i.e. where might the next eruption on the island be? The monogenetic nature of Taveuni volcanism means that the locations of new eruptive outbreaks are unpredictable and may not be related to the location of past events. However, geologic observations point to the likely areas for future events being along the southern central ridge of Taveuni, as this has been the location of almost all eruptions during the last 5000 years on the island.

The magnitude and style of activity of any future activity should conform closely to that which has happened in the past. Three main distinctive types of eruption are recognised, ranging from non-explosive lava-producing eruptions (like those on Hawaii), to mildly explosive cone-building eruptions that shower surrounding areas with tephra fall, through to highly explosive hydrovolcanic eruptions caused when rising magma encounters standing water or saturated sediments. The first two types of eruption are the most common, and both are capable of producing between 10 and 250 million m^3 of lava and tephra. Eruptions on Taveuni may continue for days or possibly for years, with either a single vent involved or a series of fissure zones or vents.

The main agencies of hazard present on the island are lava flows and tephra falls. Both these processes should not in most cases lead to great losses in life. However, both have the potential to severely damage property and infrastructure on the island – leading to great and sometimes long-term economic losses. Other more dangerous volcanic events that occur more rarely on Taveuni include hot block-and-ash flows, lahars, and pyroclastic surges associated with hydrovolcanic explosions. Other volcanic hazards include fires, lightning, volcanic gases, tsunamis, near-vent explosions and ballistics, and volcanic earthquakes.

The volcanic hazards on Taveuni have been mapped as a series of zones (Figure 2). Ground-based hazards (including: lava flows, lahars, near-vent explosions, hydrovolcanic explosions, ballistics etc.), are mapped in three zones (A-C) of decreasing degree of hazard. The greatest hazard (zone A) is confined to an area along the central ridge of Taveuni, south of Lake Tagimaucea, and to all the main drainages that radiate from this area. Tephra fall hazards (+volcanic gases) are mapped in two zones (tephra hazard zone 1 and 2) of decreasing degree of hazard. Areas facing the greatest degree of tephra-fall hazard (tephra hazard zone 1), have the greatest chance of tephra falls >20 cm. However, only small portions of this zone would ever be affected by a single eruption, and tephra distribution is primarily controlled by the vent location and wind direction.

Elements at greatest risk from volcanic activity are those located within areas with higher degrees of hazard. Population, the most important element at risk, should be relatively resilient in response to the Taveuni - type of eruptions. People should be able to escape lava flows and tephra falls. However, the most vulnerable people on the island are those that live within zones where new vents may break out (parts of southern Taveuni), or areas that may be subject to rapidly moving pyroclastic surges or lahars. The infrastructure elements considered to be a greatest risk on Taveuni include road access, agricultural production and produce transport, some water-supply installations and buildings, and tourism. Through effects on infrastructure, future eruptions of Taveuni pose a great threat to the economy of the island and its people.

The examples of eruption scenarios outlined demonstrate that the hazards during individual eruptions on Taveuni strongly depend on their location (with respect to topography, population and infrastructure), their type (e.g. lava dominated vs. hydrovolcanic), their duration, and the length and nature of precursory or warning signals. These examples and others like them should be used as thought exercises to examine the far-reaching implications of renewed volcanism on Taveuni.

Following on from this volcanic hazards assessment, strategies that could be used to reduce or mitigate volcanic risk present on Taveuni include the following items. These can be considered to be in order of their execution.

1) Geologic assessment and mapping of the volcanic hazards present on Taveuni and conducting a risk analysis (this study).

2) Dissemination of the data on volcanic hazard and risk to emergency management authorities in Fiji, including government agencies responsible for overall emergency management (e.g. Disaster Management Office, Ministry of Regional Development), other agencies directly involved (e.g. Police, Divisional authorities on Taveuni, Civil Aviation Authority of Fiji), and other NGO organisations and emergency aid providers (e.g. Red Cross).

3) Development of emergency plans to deal with a possible resumption of activity on the island; this Taveuni Volcanic Contingency Plan should include details of: warning systems, information provision, disaster management structure, operational plans, training, communication, responsibilities, and public education.

4) Dissemination of the data on volcanic hazard and risk to planning and development authorities and also international development aid agencies responsible for Fiji.

5) Formulation of strategies to mitigate potential volcanic risk on future population and infrastructure development on Taveuni (e.g. expanding tourism, road and utilities networks, village housing).

6) Development and installation of a volcanic surveillance system, coupled with a graded warning or alert-level structure that is keyed to prescribed disaster management activities (including changes to operation status, calls for advice, evacuation, and public information activities).

7) Implement a public awareness campaign with in-village and in-school visits on Taveuni, providing talks, posters, and public awareness booklets. This information should outline: volcanic hazard and risk present, what to do in an eruption, government plans in place, potential evacuation routes and signals of when to leave.

8) Revise the Taveuni Volcanic Contingency Plans on a regular (bi-annual?) basis, with periodic exercises of the plan. Carry out periodic follow-up public awareness and education activities on Taveuni, within schools and villages.

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APPENDIX 1

Radiocarbon ages that are related to volcanism on Taveuni

Date Code	Age (yrs B.P.)	Sample detail	Significance[*]	Calibrated age range[‡]	Location	Source
Wk6209	340 ± 70	Charcoal in soil (with lava clasts) beside South Cape lava flow	Direct age on passage of youngest South Cape lava flow (Tutu Fm.)	1460-1660 AD	E 179° 56.012’ S 17° 00.340’	Cronin, this study
GaK-2507	340 ± 80	Anthropologic charcoal beside Tutu lava flows	Min age for Tutu lava flows (Tutu Fm)	1450-1660 AD	W 179° 59.50’ S 16° 48.17’	Frost, 1974
NZ5598C	499 ± 162	Soil charcoal near Tutu lava flows	Fires related to Tutu lava flows (Tutu Fm.)	1300-1630 AD	W 179° 59.23’ S 16° 49.57’	Shepherd and Neall, 1991
Wk6004	510 ± 60	Anthropologic charcoal beneath Tutu lava flows	Max age for Tutu lava flows (Tutu Fm.)	1402-1444 AD	180° 00.00’ S 16° 49.50’	Cronin, this study
Wk6006	640 ± 60	Peat below Des Voeux tephra	Max age for Des Voeux tephra (Tavuyaga Fm.)	1290-1410 AD	W 179° 58.082’ S 16° 50.832’	Cronin, this study
GaK-2411	710 ± 80	Anthropologic charcoal above Tavuyaga tephra	Min age for Tavuyaga tephra (Tavuyaga Fm)	1260-1390 AD	E 179° 55.00’ S 17° 00.08’	Frost, 1974
GaK-2414	710 ± 80	Anthropologic charcoal above Vatuwiri lavas	Min age for Vatuwiri lava flows (Tavuyaga Fm.)	1260-1390 AD	E 179° 53.67’ S 16° 57.67’	Frost, 1974
GaK-2413	740 ± 70	Anthropologic charcoal above Vatuwiri lavas	Min age for Vatuwiri lava flows (Tavuyaga Fm.)	1235-1300 AD	E 179° 54.55’ S 16° 56.92’	Frost, 1974
Wk6729	850 ± 130	Soil at base of Vana Kei Vuna cone	Min age for Vana Kei Vuna cone and tephra (Tavuyaga Fm.)	1020-1290 AD	E 179° 56.955’ S 16° 57.536’	Cronin, this study
Wk6213	1020 ± 130	Peat at base of explosion crater and above DV1 tephra?	Min age for crater explosion (Tavuyaga Fm.)	890-1170 AD	W 179° 58.082’ S 16° 50.832’	Cronin, this study
Wk6214	1090 ± 60	Soil near base of Tavuyaga crater	Min age for Tavuyaga tephra and cone (Tavuyaga Fm.)	890-1020 AD	E 179° 55.508’ S 16° 59.790’	Cronin, this study
Wk6727	1420 ± 60	Peat below tephra within Drano Palo crater	Max age for Soqulu tephra (Tavuyaga Fm.)	600-670 AD	W 179° 58.910’ S 16° 51.480’	Cronin, this study
Wk6211	1460 ± 160	Organic soil at base of Coloci crater, above Tavuyaga tephra	Min age for Tavuyaga tephra and Coloci cone and tephra (Tavuyaga Fm.)	420-690 AD	E 179° 55.816’ S 16° 58.685’	Cronin, this study
Anu-3811	1500 ± 120	Peat above Des Voeux 1 tephra	Min age for Des Voeux tephra (Tavuyaga Fm.)	410-640 AD	W 179° 56.26’ S 16° 49.49’	Southern, 1986
Wk6010	1560 ± 60	Charcoal below Tavuyaga tephra, fires with the eruption	Direct age for Tavuyaga tephra (Tavuyaga Fm.)	420-600 AD	E 179° 55.491’ S 16° 59.220’	Cronin, this study
Wk6726	1620 ± 50	Charcoal below Waiyevo lavas	Direct age for Waiyevo lavas and Des Voeux tephra (Tavuyaga Fm.)	400-540 AD	W 179° 59.370’ S 16° 49.250’	Cronin, this study
NZ5599C	1645 ± 55	Wood below Des Voeux 1 tephra	Max age for Des Voeux tephra (Tavuyaga Fm.)	380-450 AD	W 179° 57.69’ S 16° 50.38’	Shepherd and Neall, 1991

Wk6725	1650 ± 60	Charcoal within Des Voeux 1 tephra	Direct/max age for Des Voeux tephra (Tavuyaga Fm.)	340-450 AD	W 179° 57.860’ S 16° 50.410’	Cronin, this study
Wk6009[†]	1750 ± 65	Charcoal below Likuvausomo lavas	Direct age of Likuvausomo lava flows, max age of Likuvausomo tephra (Tavuyaga Fm.)	230-400 AD	E 179° 57.217’ S 16° 53.00’	Cronin, this study
Wk6732[†]	1836 ± 61	Anthropologic charcoal in soil below Naqara lavas	Maximum age for Naqara lava flow (Tavuyaga Fm.)	120-320 AD	W 179° 58.386’ S 16° 46.852’	Cronin, this study
GaK-2412	2050 ± 150	Anthropologic charcoal below Tavuyaga tephra	Max age for Tavuyaga tephra and min age for Navolivoli cone (Tavuyaga Fm.)	290BC-100AD	E 179° 55.00’ S 17° 00.08’	Frost, 1974
Wk6208	2180 ± 70	Anthropologic charcoal within a paleosol below tephric sediments	Max age of tephric sediment influx (nearby eruption), oldest date for humans on Taveuni.	370-110 BC	E 179° 59.253’ S 16° 58.543’	Cronin, this study
Wk6733[†]	2300 ± 58	Charcoal within the Base of Ura tephra	Direct age on the Ura tephra and minimum age for the Ura lava flows (Ura Fm.)	400-250 BC	E 179° 56.432’ S 16° 54.951’	Cronin, this study
Wk6734	2340 ± 60	Peat at the base of an axial crater nth of Uluiligalau	Min age of eruption vents along the central axis Nth of Uluiligalau. (Ura Fm.)	406-377 BC	W 179° 59.990’ S 16° 53.260’	Cronin, this study
Wk6728	4520 ± 70	Peat at the base of Drano Palo crater, upper Soqulu	Min age of eruptive vent for Soqulu 1 lavas (Narata Fm.)	3360-3340 BC	W 179° 58.910’ S 16° 51.480’	Cronin, this study
Wk6008	4830 ± 170	Peat below Nadawa tephra, within Nayavuloa crater	Max age for Nadawa tephra and lava and min age for Nayavuloa cone (Narata Fm.)	3790-3370 BC	E 179° 59.582’ S 16° 52.114’	Cronin, this study
Wk6731	5890 ± 80	Wood/peat at base of Narata crater	Min age for Narata crater/tephra and Narata lavas (Narata Fm.)	4900-4690 BC	W 179° 53.660’ S 16° 43.370’	Cronin, this study
Wk6730	7081 ± 70	Soil at the base of the youngest Qila cone	Min age for the youngest cone in the Qila area (Tuvumaca Fm.)	5980-5840 BC	W 179° 54.984’ S 16° 45.358’	Cronin, this study
Wk6212	7812 ± 61	Peat at base of fault swamp, Sth Tagimaucea basin	Min age for Tagimaucea tephra and Des Voeux lavas, min age for fault scarp onset (Tuvumaca Fm.)	6630-6490 BC	W 179° 56.622’ S 16° 50.539’	Cronin, this study
Anu-3812	14 120 ± 370	Peat near base of Tangimaucea basin	Min age of Tangimaucea basin, possibly volcanic		W 179° 56.26’ S 16° 49.49’	Southern, 1986
Wk6011	>45 000	Coral within Koronitevora tuff cone	Max age of Koronitevora phreatomagmatic eruptions		E 179° 57.315’ S 17° 00.00’	Cronin, this study

* Unit names are informal mapping units derived from Objective 1 of this study.

[†] Samples dated using Accelerator Mass Spectrometry (AMS) at the Rafter Radiocarbon Dating Laboratory, I.G.N.S. Lower Hutt, New Zealand. All other samples are conventional beta-counting dates from the University of Waikato Radiocarbon Dating Laboratory, Hamilton, New Zealand.

[‡] Calibrated ages <10 000 B.P. calculated using OxCal v.3.0, Bronk-Ramsay (1998) and calibrated using curve of Stuiver, Long and Kra (1993).

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